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JPRS: 16,703

17 December 1962

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DOSIMETRIC CONTROL ON ATOMIC SHIPS

by D. V. Lyush and B. N. Nikolayev

- USSR -

U. S. DEPARTMENT OF COMMERCE
OFFICE OF TECHNICAL SERVICES
JOINT PUBLICATIONS RESEARCH SERVICE
Building T-30
Ohio Drive and Independence Avenue, S.W.
Washington 25, D. C.

Price: $10.50

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[Following is the translation of the Russian-language book by D. V. Lyush and B. N. Nikolayev entitled, Dozimetricheskiy Kontrol' Na Atomnykh Sudakh (English version above) Leningrad, State-Union Publishing House of the Shipbuilding Industry, 1962, pp 1-132.]

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The present work deals with the problems of radiation safety and dosimetric control methods on vessels with nuclear power plants. It includes the necessary information from the fields of physics and nuclear technology. Also included is a brief description of the system of radiation safety and dosimetric control on the atomic icebreaker "Lenin", along with some information on radiation safety on foreign nuclear vessels.

The book is designed for engineers and technicians in the shipbuilding industry and the Navy, and will likewise be useful to students of shipbuilding institutes.

FOREWORD

The wide application of atomic technology in general and nuclear power in particular has also been extended to modern shipbuilding. Soviet shipbuilding science is in the vanguard of world thinking in this branch of technology.

The atomic icebreaker "Lenin" is the world's first merchant vessel with a nuclear power plant (NPP). This is the crowning achievement of scientists, designers, and workers in the shipbuilding industry and other industries of the USSR. Following in the footsteps of the Soviet Union, the US designed and built a nuclear passenger-cargo vessel, Sweden began construction of a large tanker, etc. It can be stated confidently that nuclear shipbuilding will develop even more with the accumulation f experience in the use of economical and efficient ship reactors.

However, a major portion of the engineering forces in the shipbuilding industry and the Navy has little knowledge of the basic problems of nuclear technology, and moreover, lacks a clear conception of the specifics of exploiting nuclear power plants. Frequently, they harbor an exaggerated fear of the danger of operating such plants. This feeling has been fostered by the appearance of accounts in the press dealing with difficulties and tieups in the testing of nuclear submarines in the US.

The literature on the problems of nuclear safety on vessels with NPP consists of just several papers presented by Soviet scientists before the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958).

Our book represents the first attempt to generalize the problems of dosimetric control and radiation safety on NPP vessels. It contains a systematic presentation of materials published in Soviet and foreign periodicals, with an account of the latest achievements in the field of ionizing radiation dosimetry.

The authors have striven to present the material in a popular fashion, without overloading the test with mathematics, while preserving the rigor of the formulations.

The content of the book must demonstrate that with a correctly planned NPP installation and the realization of proper control, its exploitation under ship conditions does not present any fundamental difficulties or dangers.

The first chapter contain a brief presentation of the basic notions of nuclear physics and technology to an extent necessary for the understanding of the physical essence of the relevant phenomena and processes.

The subsequent chapters contain information on the forms of radiation danger and means of combatting them, as well as on biological protection and dosimetric control methods on nuclear ships.

The last two chapters contain a brief description of the system of dosimetric control aboard the atomic icebreaker "Lenin" and some information on radiation safety on foreign NPP vessels.

The present work does not deal with the problems of radiochemical analysis and deactivation arising in the exploitation of nuclear reactors, since these are independent aspects of the radiation safety problem.

The authors consider it their pleasant duty to extend sincere thanks to V.I. Zadantsev and Yu.V. Sivintsev for their considerable assistance and advice.

The authors would also appreciate all critical remarks on the work; these should be addressed to: Leningrad D-65, Dzerzhinskiy Street (Ulitsa Dzerzhinskogo) 10, Sudpromgiz (State Union Publishing House of the Shipbuilding Industry).

Chapter I

THE NOTION OF IONIZING RADIATION

1. Radioactivity

All natural bodies are made up of atoms and molecules which are in a state of continuous motion.

The atoms in elements, combining in various ratios, form an enormous variety of compounds. The smallest particle of a compound which retains the specific chemical properties of the compound is called a molecule. The atom is the smallest particle in ordinary matter which remains unchanged in chemical reactions. It constitutes a complex electrically-neutral system made up of a positively-charged nucleus and negatively-charged electrons in motion about the nucleus in closed orbits which constitute the electron shell.

The nucleus of an atom consists of a definite number of positively-charged particles -- protons, and uncharged neutral particles -- neutrons.

The proton is the nucleus of the lightest element (hydrogen) and has a mass approximately equal to the mass of the neutron. The positive charge of the proton is equal in magnitude to the negative charge of the electron.

In nuclear physics, protons and neutrons are frequently referred to as nucleons.

Since the atom is electrically neutral, the number of electrons orbiting the nucleus is equal to the number of protons making up the nucleus of the atom of a given element and is the main characteristic of the given element. The changing of the number of protons in the nucleus signifies a transition from one substance to another. For example, the hydrogen nucleus consists of one proton ($z=1$), the boron nucleus contains five protons ($z=5$), cadmium -- 48 ($z=48$), uranium -- 92 ($z=92$). It has been established that the nuclear charge z corresponds to the number of the element in the Periodic Table, while the peculiarities of electron shell structure determine the periodicity of repetition of their chemical properties.

Another important property of atomic nuclei is their mass, which by analogy with the charge is expressed in special units called atomic mass units, approximately equal to the mass

of the proton or neutron. The mass number A of any nucleus represents the sum of protons and neutrons it contains.

As distinct from the charge z, whose increase or decrease is always accompanied by a change in the chemical properties of a substance, the variation of atomic number A can also be due to changes in the number of neutrons in the nucleus. Since such changes leave the number of protons, i.e., the nuclear charge z constant, the new nuclei due not differ chemically from their "neighbors" in the Table. At the same time, a different number of protons and neutrons in the nucleus characterizes a different class of nuclei which differ in their physical properties. Such nuclei which have the same charge (number of protons in the nucleus) but differ in mass (number of neutrons) are called isotopes, i.e., occupying the same position in the Periodic Table (from the Greek word "topos", meaning "place").

Atomic nuclei are usually denoted by the symbol

$$_zX^A$$

where z is the atomic number of the nucleus;
X is the name of the element;
A is the mass number.

For example, the hydrogen nucleus is written as $_1H^1$, the sodium nucleus is $_{11}Na^{23}$, etc.

The number of protons making up a nucleus determines the size of the positive nuclear charge, and therefore the number of electrons in the electron shell of the atom. It also determines the atomic number of the element z. Writing this subscript in specifying elements helps in recording nuclear reactions.

The radius r of an atomic nucleus can be evaluated approximately with the aid of the equation

$$r = 1.5 \cdot 10^{-13} A^{1/3},$$

where A is the mass number of the nucleus equal to the sum of protons and neutrons it contains.

Hence we can calculate that the radius of the nucleus of the lightest element -- hydrogen -- is equal to 10^{-13} cm (approximately), while the nuclear radius of one of the heaviest elements such as uranium is $\sim 10^{-11}$ cm.

In the course of studies of nuclear properties, it was established that some nuclei spontaineously, without any external influences, disintegrate and emit particles, forming nuclei of other types as a result. This phenomenon was called radioactivity.

As early as in 1896 the physicist Becquerel found that uranium compounds emit invisible rays which blacken a photosensitive plate. Two years later it was discovered that the new elements (radium and polonium) discovered by Pierre and Marie Curie likewise exhibited radioactivity analogous to that of uranium compounds, but stronger in intensity.

Studies with the aid of a magnetic field have shown that three types of radiation are in evidence in the disintegration of heavy elements: positively-charged alpha particles, negatively-charged beta particles, and electromagnetic radiation of very short wavelength -- gamma rays. The common property of all three forms of radiation is its ability to ionize atoms in passing through matter, i.e., to remove one or more electrons from the shells of neutral atoms. Because of this, all three types of radiation are referred to as ionizing radiation.

Let us consider some of the other properties of radiation which accompanies the decay of radioactive atoms.

Alpha particles have a positive electrical charge equal in absolute value to two electron charges, and a mass equal to that of the helium nucleus. The penetrating power of alpha particles is determined by their interaction with nuclei and atoms of matter and is measured according to their range in a given substance. Usually, the range is measured in centimeters. For alpha particles of naturally radioactive materials, the range in air does not exceed 10 cm, while in solids and liquids it is extremely small and does not exceed tens of microns. For example, several sheets of paper are sufficient to fully absorb most of the alpha particles emitted by radioactive elements.

As distinct from alpha particles, beta particles of comparable energies, which are essentially fast electrons, are characterized by much greater ranges in air. Several sheets of paper are no longer adequate to block them; something like a sheet of aluminum several millimeters thick is required. The thickness of material required for total absorption will be strongly dependent on the initial energy of the beta particle and the density of the absorber material.

Gamma rays constitute a stream of photons which are no different than X-rays. For the same wavelength, the properties of these two types of radiation are the same; the only difference is in the source: photons emitted by a nucleus are called gamma rays (gamma quanta), while photons produced by the slowing of electrons in a field of atomic nuclei are called X-rays.

As distinct from alpha and beta particles, gamma particles have a high penetrating power. High-energy gamma rays, with energies on the order of millions of ev (electron volts) (see note) can pass even through several tens of centimeters of lead, despite the fact that lead, just as other

elements with a high atomic number, is a more effective absorber of gamma radiation than light elements. [Note: An electron volt is the unit of energy acquired by an electron in being accelerated through a potential difference of one volt].

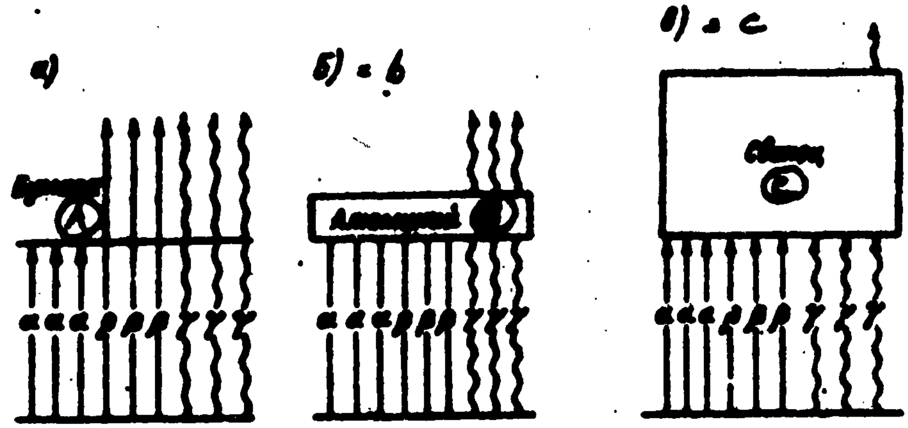

Figure 1. Relative penetrating power of alpha and beta particles and gamma rays. A = Paper; B = Aluminum; C = Lead.

Let us imagine a radioactive source which emits alpha, beta, and gamma rays (Fig 1). Over the source we place an absorber consisting of several sheets of ordinary paper (Fig 1a). The alpha particles are absorbed by the paper, but the betas and gammas pass through without any significant loss of energy. Fig 1b shows the effect of an absorber consisting of several millimeters of sheet aluminum. In this case, the aluminum filters out or absorbs the alphas, and betas, while the gammas are just somewhat weakened. Finally, Fig 1c shows that an aborbing layer of several centimeters of lead considerably reduces the intensity of gamma rays, but still does not stop them completely. As distinct from alphas and betas, gamma rays are frequently called penetrating radiation.

There is yet another form of radiation -- neutrons produced during the operation of nuclear reactors. The properties of these particles will be considered later.

In the earliest stages of research on the properties of radioactive atoms it was discovered that their acitivity drops off with time.

The course of the radioactive decay process for any material consisting of a given number of similar atoms can be described with the aid of a certain constant called the half-life. If at a given instant we have a certain number of atomic nuclei of type A, then after the half-life period has

elapsed, one half will have been transformed into atomic nuclei of a new type B. After a period of two half-lives, one-fourth of the original type A nuclei will remain, after three half-lives, one-eighth type A nuclei are left, etc.

A new substance can also turn out to be radioactive and in turn be transformed to a third substance C. In such cases we say that materials A, B, and C constitute a radioactive family.

If T is the half-life, then after a time t, the remaining number of the original number of atoms N_o will be

$$N = N_o \cdot e^{t/T}.$$

Along with the half-life T, we frequently make use of another quantity λ which is called the decay constant and is given by

$$N = N_o e^{-\lambda t} \qquad (1)$$

(which is called the radioactive decay law).

Hence

$$\lambda = (1/T)\ln 2 = 0.693/T.$$

The radioactive constant is a measure of the instability of atoms and is defined as the fraction of nuclei decaying per unit time for the given radioactive substance. The minus sign in (1) means that the number of decaying nuclei decreases with time; the dimensions of the decay constant are $[\text{time}]^{-1}$.

Using as an example the decay of radioactive carbon we will show how it results in the production of a nitrogen isotope accompanied by the emission of an electron:

$$_6C^{14} \rightarrow {}_7N^{14} + \beta,$$

i.e., carbon $_6C^{14}$ decays with the emission of a single beta particle, an electron, to become nitrogen $_7N^{14}$.

Similarly to chemical reactions, the radioactive decay process is recorded in the form of symbolic equations. On the left-hand side we write the symbol for the isotope or initial nucleus; to the right of the arrow are written the symbols for the final decay products. The following notation is used: β -- electron, n -- neutron, p -- proton, γ -- gamma quantum.

The concept of activity is introduced to compare various radioactive materials.

Let us denote by N the number of nuclei of a radioactive material in some sample; then the number of nuclei decaying per second will be $N\lambda$, where λ is the familiar decay constant. The product $N\lambda$ represents the activity of the given sample.

If we denote by C_0 the initial activity, and by C the activity at instant t, then according to the decay law we shall have the relation

$$C = C_0 e^{-\lambda t}.$$

In determining the quantity of radioactive material (activity) the most widely-used unit is the "curie", in honor of Pierre and Marie Curie. The curie is the quantity of radioactive material in which $3.7 \cdot 10^{10}$ disintegrations occur per second. Approximately the same number of disintegrations occur, for example, in a gram of radium each second. Thus, the activity of one gram of radium is practically equal to one curie.

2. The Concept of the Radiation Dose. Maximum Permissible Doses and Concentrations

Emissions from radioactive elements and the products of nuclear reactions, such as gamma rays, neutrons, protons, alpha and beta particles, all produce ionization in passing through matter.

Charged particles produce ionization along their path directly through the action of the electric field on the orbital electrons of the target material. Gamma rays and neutrons do not produce ionization directly. However, so-called secondary electrons arising in the absorption of gamma rays by matter, do result in ionization.

The irradiation of live tissues with ionizing radiation over specific, so-called maximum permissible levels which will be indicated below, can be dangerous to human life and health. This is due to damage to cells which is the result of the interaction of radiation with the atoms in the biological tissue.

The danger from which the operating personnel of nuclear power installations must be protected can be twofold: in the first place, external radiation, and secondly, the more concealed and pernicious danger of internal irradiation as a result of the contamination of air, water, and food.

The penetrating power of alpha and beta particles is not great, so that in operating a nuclear reactor there is no need for special measures to protect personnel from external irradiation by these rays. In these cases, as will be shown below, it is necessary to deal merely with protection from neutrons and gamma rays.

However, alpha and beta rays assume major importance in the presence of the second type of danger, i.e., with the possibility of radioactive substances entering the organism.

For a quantitative evaluation of the effects of ionizing radiation on the irradiated medium we use the notion of the absorbed radiation dose.

The absorbed dose is defined as the radiation energy absorbed by a unit mass of irradiated medium:

$$D = E/M,$$

where D is the absorbed radiation dose;
E is the energy absorbed by the irradiated matter;
M is the mass of the irradiated material.

The amount of energy absorbed by a unit mass of irradiated material per unit time is accordingly called the dose rate:

$$P = D/t,$$

where P is the dose rate;
D is the radiation dose;
t is the duration of irradiation.

As the practical unit for measuring the radiation dose we use the roentgen (r) -- the dose of X-rays or gamma rays in the air with which the concomitant corpuscular emission per 0.001293 gram of air will produce ions in the air carrying a charge of one electrostatic unit of electricity of each sign. The number 0.001293 is the mass in grams of one cubic centimeter of air at 0°C and 760 mm Hg.

The thousandth and millionth fractions of a roentgen are written mr and mcr and are called the milliroentgen and microroentgen.

The X-ray or gamma-ray dose is a measure of radiation based on its ionizing ability. By the absorbed radiation dose we mean the energy of the ionizing radiation absorbed by a unit mass of material. The unit of absorbed radiation, the rad, is equal to 100 ergs per gram of irradiated material.

Let us cite some data in order to indicate the magnitude of the one-roentgen dose.

Natural conditions -- cosmic rays -- 0.018 mr/day.

Natural conditions -- naturally radioactive substances inside and outside the human body -- 0.001 r/day.

Maximum permissible dose of total occupational irradiation for the human body -- 0.3 r/week.

Maximum single dose permissible in total irradiation of human body -- 3 r.

Radiation sickness with overall irradiation of the human body -- 100 r and up.

Minimal absolutely fatal dose with overall irradiation of the human body -- 600 r.

Therapeutic doses (local irradiation) -- up to 15,000 r.

At the present time, in connection with the practical necessity of determining the intensity of beta rays and neutron beams, the concept of the physical equivalent of the roentgen, the rep (roentgen equivalent, physical), has been introduced. A 1-rep dose corresponds to the ionization for which, regardless of the nature of the ionizing particles, about $2 \cdot 10^9$ ion pairs are formed in one cubic centimeter of air at $t = 0°C$ and 760 mm Hg; this is equal to one electrostatic unit of charge.

The situation, however, is complicated by the fact that, as was shown by studies on experimental animals, various biological effects are produced by the same degree of ionization of air produced by different types of radiation. It was necessary to introduce the notion of relative biological effectiveness (RBE) of various types of ionizing radiation and the unit called the reb (roentgen equivalent, biological).

The reb is the amount of energy in a type of radiation whose biological effect is equivalent to that of 1 r of X-rays or gamma-rays. The reb is different for various types of radiation.

The relative biological effectiveness of various types of radiation is a quantity equivalent to the effect on the organism of a single maximum permissible daily dose of occupational radiation.

Let us cite some data on the relative biological effectiveness of various types of radiation; our unit is the biological effectiveness of X-rays with a boundary energy of 200 kev (Table 1).

Table 1

Relative Biological Effectiveness (RBE) and Maximum Permissible Doses of Radiation From Various Types of Ionizing Radiation

Вид излучения A	ОБЭ B	Предельнодопустимые дозы в сутки C	
		бэр D	фэр или р E
Рентгеновские лучи F	1	0,017	0,017
Гамма-излучение G	1		0,017
Бета-излучение H	1		0,017
Альфа-частицы, протоны I	10		0,0017
Тепловые нейтроны J	5		0,0034
Быстрые » K	10		0,0017

A = Isotope; B = RBE; C = Maximum permissible daily doses; D = reb; E = rep or r; F = X-rays; G = Gamma rays; H = Beta rays; I = Alpha particles, protons; J = Thermal neutrons; K = Fast neutrons.

As was pointed out above, radioactive isotopes entering an organism are a particularly great danger. This is because of the difficulty and slowness of their removal from the organism and the direct action of their radiation on the vital organs of the system.

In examining the questions having to do with the content of radioactive materials in the organism, we introduce the concept of the so-called critical organ, i.e., an organ on which the effect of a given concentration of a radioactive element determines the basic portion of the biological effect. It is introduced because of the fact that various elements tend to concentrate in some particular organ or tissue, as a result of which their action on this organ or tissue has decisive importance.

The maximum permissible concentration of radioactive isotopes in a critical organ is calculated assuming a maximum permissible dose of 0.3 reb/week, taking into account the energy of radioactive decay, the average weight of the critical organ, the half-life, and the natural biological elimination of the isotope from the organism in waste matter.

Table 2

Maximum Permissible Concentrations of Some Radioactive Isotopes in the Water of Open Vessels and the Air of Working Areas

Изотоп (A)	Предельнодопустимая концентрация, кюри/л (B)	
	в воде (C)	в воздухе (D)
Стронций-90 (E)	$3 \cdot 10^{-11}$	$3 \cdot 10^{-13}$
Йод-131 (F)	$6 \cdot 10^{-10}$	$9 \cdot 10^{-12}$
Ксенон-133 (G)	—	$1 \cdot 10^{-8}$
Полоний-210 (H)	$2 \cdot 10^{-11}$	$1 \cdot 10^{-11}$
Радий-226 (I)	$5 \cdot 10^{-11}$	$3 \cdot 10^{-14}$
Плутоний-239 (J)	$5 \cdot 10^{-11}$	$2 \cdot 10^{-15}$

A = Isotope; B = Maximum permissible concentration, curies/liter; C = in water; D = in air; E = Strontium-90; F = Iodine-131; G = Xenon-133; H = Polonium-210; I = Radium -226; J = Plutonium-239.

The maximum permissible concentration in air and water is determined under the assumption that the amount of water consumed by a human being is about 2200 cc/day, while the excreted amount is $2 \cdot 10^{7}$ cc/day. Table 2 shows the maximum permissible concentrations of certai radioactive isotopes in air and water.

3. Nuclear Binding Energy and Nuclear Reactions

Nuclear binding energy. Shell electrons are bound in the atom by the electrostatic attraction of their negative charge to the positive charge on the nucleus. The binding energy of these electrons and the nucleus is immeasurably smaller than the binding energy between the nuclear particles, which is one the order of several million electron volts (mev). The high binding energy of neutrons and protons in atomic nuclei explains their enormous stability.

At first glance it might seem that atomic nuclei cannot be stable since the protons contained in them must repel each other since they carry the same charge. The energy of this repulsion is given by Coulomb's law. However, the stability of most atomic nuclei is evidence of the fact that when protons approach, attractive forces are superimposed on the repulsive force which increase rapidly the closer the approach. At distances of 10^{-13} cm they significantly exceed Coulomb repulsion. The same forces arise when protons approach neutrons. These attractive forces between nucleons are called nuclear forces.

There is as yet no completely adequate theory of nuclear forces, nor is everything known about their properties. However, there is no need to determine the binding energy for a nucleus -- here we need merely make use of the energy conservation law. If we were able to pull apart all of the nucleons one by one without endowing them with additional kinetic energy, then this would require an amount of work equal to the nuclear binding energy. In accordance with the energy conservation law, the same amount of energy must be released upon the formation of a nucleus from these nucleons regardless of how it occurs. This energy is made up by the change in mass of the coalescing nucleons. The law of interaction of mass and energy, theoretically justified by Eistein and subsequently confirmed by experiments on nuclear reactions, is embodied in the formula

$$E = mc^2,$$

where E is the energy;
m is mass;
c is the velocity of light.

From this relation it follows that one atomic mass unit (1 amu = 1/16 of the mass of the basic oxygen isotope $_8O^{16}$ and constitutes $1.657 \cdot 10^{-24}$ g) is equivalent to

$$E = 1.657 \cdot 10^{-24} (2.99790 \cdot 10^{10})^2 = 1.49 \cdot 10^{-3} \text{ erg} = 931 \text{ Mev}.$$

If the energy E released upon the creation of an atomic nucleus is large, then the mass defect

$$\Delta m = E/c^2$$

has a noticeable value. This defect is called the mass defect. In other words, the mass defect is the difference between the theoretical sum of the masses of electrons and nucleus making up the given atom or nucleus and the mass determined experimentally.

Let z protons and A-z neutrons form an atom of a nucleus with a mass m. Let us denote the mass of the proton by m_p and the mass of the neutron by m_n.

Then the mass defect

$$\Delta m = zm_p + (A-z)m_n - m.$$

If the masses are expressed in amu, then the nuclear binding energy (in mev)

$$E = 931\Delta m = 931[zm_p + (A-z)m_n - m].$$

In practice, the binding energy in mev is more easily calculated from the formula

$$E = 931[zm_H + (A-z)m_n - M],$$

in which $m_H = 1.00814$ amu is the mass of the hydrogen atom; $m_n = 1.00895$ amu is the mass of a neutron; M is the mass of the isotope in amu.

As an example, let us determine the mass defect and the nuclear binding energy for the isotope of uranium-235 whose mass in amu is equal to 235.2:

$$\Delta m = 92\cdot 1.00814 + (235-92)1.00895 - 235.2 = 1.90 \text{ amu};$$

$$E = 931\cdot 1.90 = 1770 \text{ mev}.$$

Hence the binding energy per nucleon is $1770/235 \approx 7.5$ mev.

<u>Nuclear reactions</u>. Under certain conditions, certain atomic nuclei can react with other nuclei. As distinct from chemical reactions, when there is a rearrangement of the outer electron shells of the atom, the nuclei themselves undergo restructuring in nuclear reactions. In many cases this leads to the transmutation of certain chemical elements into others.

Similarly to chemical reactions, nuclear reactions are written in the form of symbolic equations. For example, the reaction of neutron capture by hydrogen which leads to the formation of heavy hydrogen (deuterium), is written as

$${}_1H^1 + n \longrightarrow {}_1H^2 + \gamma$$

or

$$H^1(n, \gamma)H^2.$$

It is easy to see that inasmuch as the total number of nucleons (protons and neutrons) is conserved in nuclear reactions, the sum of the mass numbers of the initial nucleus and interacting particle is equal to the sum of the mass numbers of the final reaction products. Similarly, in accordance with the well-known law of charge conservation, the sum of the subscripts in the symbols before and after the reaction remains the same.

Nuclear reactions can arise in the irradiation of substances with neutrons, protons, alpha particles, etc. The probability of the occurence of nuclear reactions is characterized with the aid of a certain quantity called the effective reaction cross-section and expressed in units of area; i.e., the bombarded nucleus is assigned an effective target area which it is necessary to hit in order for the reaction to occur.

Let us explain this in greater detail. Upon the passage of any particles, such as neutrons, through matter, various types of interactions may take place between them and the nuclei of the substance. However, some of the neutrons will pass through the substance without any interaction with its atoms. If the substance is homogeneous, while the neutrons are of equal energy and direction, the probability of participation in the nuclear reaction must be the same for all neutrons and all atoms of the substance irradiated with the neutron beam. Hence it follows that the law which quantitatively determines the interaction of neutrons and nuclei must have a purely static character. The number of neutrons interacting with atoms must be proportional to the number N of neutrons in the beam, the number n of atoms per unite volume of the substance, and the free path of the neutrons in the substance.

Denoting by N_o the number of neutrons falling at right angles on a flat layer of material of thickness x, and by N_x the number of neutrons emerging from the layer, it is possible to show that

$$N_x = N_o e^{-\sigma n x},$$

where σ is the proportionality coefficient.

Since n has dimensions of cm^{-3} and x is in cm, the coefficient of proportionality σ must be in cm^2. It is called the effective nuclear cross-section and represents a measure of the probability of the given reaction.

In the case of a nuclear reactor, the most important reactions are those involving the interaction of neutrons with matter.

The collision of neutrons with the nuclei of bombarded atoms can be classified as numerous types of nuclear reactions, among which the most important are the following.

1. Nuclear fission (n,p) in which the nucleus of a heavy element following neutron capture splits up into two fragments (approximately equal in mass) with the emission of two or three neutrons.

2. Radiation capture (n, γ) -- the most probable process for thermal and slow neutrons.

3. Elastic scattering (n,n) -- scattering without alteration of the structure of the bombarded nucleus, in which the kinetic energy of the neutron-nucleus system remains constant.

4. Inelastic scattering (n,n') -- scattering in which there occurs a nuclear interaction between the bombarded nucleus with a neutron, and a subsequent release of the neutron with an altered kinetic energy.

A special case of interaction between a neutron and an atomic nucleus is the scattering of neutrons by atomic nuclei. As we shall see below, this phenomenon is important in reactor operation.

To conclude this section, let us cite several examples of nuclear reactions.

Nuclear fission:

$$_{92}U^{235} + {_0}n^1 \rightarrow {_{36}}Kr^{91} + {_{56}}Ba^{142} + 3{_0}n^1;$$

$$_{94}Pu^{239} + {_0}n^1 \rightarrow {_{40}}Zr^{98} + {_{54}}Xe^{140} + {_0}n^1.$$

Radiation capture:

$$_1H^1 + {_0}n^1 \rightarrow {_1}H^2 + \gamma;$$

$$_{27}Co^{59} + {_0}n^1 \rightarrow {_{27}}Co^{60} + \gamma.$$

(n,p) reaction:

$$_7N^{14} + {_0}n^1 \rightarrow {_6}C^{14} + {_1}H^1;$$

$$_{28}Ni^{58} + {_0}n^1 \rightarrow {_{27}}Co^{58} + {_1}H^1.$$

Chapter II

REACTORS -- SOURCES OF IONIZING RADIATION

The nuclear reactor is the heart of a nuclear power plant; it produces the energy which puts machines in motion: turbines, generators, etc. The operation of a nuclear reactor is accompanied by the formation of powerful streams of ionizing radiation.

It is necessary to have a clear idea of the process involved in the appearance of ionizing radiation in a reactor and other elements of a nuclear power installation in order to be able to assure reliable radiation safety to the operating personnel.

4. The Fission Reaction

The fission process is most easily explained by appealing to the so-called drop model of the nucleus. It is known that due to the mutual attraction of molecules in the surface layer of a drop of water, the drop assumes a spherical form stable to deforming forces.

It is supposed that an analogous phenomenon occurs in the atomic nucleus. Quite naturally, if a drop or nucleus is supplied with enough energy, it is likely that it will split up into two smaller parts. In this process, a significant role is played by the nuclear binding energy in the form of Coulomb repulsive forces and surface tension forces. The deformation of the nucleus under the action of a bombarding particle first increases the binding energy to a maximum due to the enlargement of the surface and the surface forces. Then the binding energy diminishes rapidly due to Coulomb forces (charged particles drawn apart to great distances), and this is no longer compensated by an increase in the surface binding forces. There is a fission process (Fig 2).

In each of the fragments formed in the splitting of an unstable nucleus, the attractive forces already outweigh the repulsion, and the energy of the new system is lower than that of the original one. For this reason it can be assumed that some amount of energy must be released in the formation of two fragments.

The fission of uranium nuclei is accompanied by the fromation of fission fragments with a mass greater than that of hydrogen by 72-159 times. They are the nuclei of elements located in the middle portion of the Periodic Table.

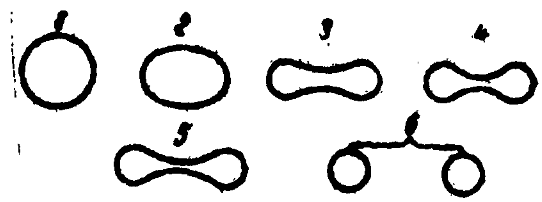

Figure 2. Schematic representation of the process of the division of a nucleus into two "drops" (fragments).

Because of the fact that the nuclei of heavy elements contain a larger number of neutrons in comparison with the nuclei of atoms in the middle portion and beginning part of the Periodic Table, their fragments likewise have an excess of neutrons which accounts, in particular for their beta-activity. Such beta-active nuclei give rise to an enormous variety of chain decay reactions [note: the term <u>decay chain</u> refers to a series of isotopes formed as a result of the successive decay of each of the decay fragments until the formation of a stable isotope]. For example the fragment $_{36}Kr^{92}$ formed in uranium decay has the following decay chain:

$$_{36}Kr^{92} \xrightarrow[(3.0\ sec)]{\beta^-} {}_{37}Rb^{92} \xrightarrow[(80\ sec)]{\beta^-} {}_{38}Sr^{92} \xrightarrow[(2.7\ hours)]{\beta^-} {}_{39}Y^{92} \xrightarrow[(3.6\ hours)]{\beta^-} {}_{40}Zr^{92}\ \text{(stable)}.$$

The final yield of any fission product, i.e., its percentage ratio to the other products, is defined as the relative number of fission events leading to the formation of a given fragment. Fig 3 shows the yield of various fission fragments of uranium-235 (as a percentage) upon neutron irradiation.

The most important result of fission is the release of energy. It is known that for fission fragments with mass numbers 70-160 the binding energy amounts to an average of 8.35 mev, and for the uranium atom, as was shown above, to 7.5 mev per nucleon. The difference between the total binding energy of the uranium nucleus containing 235 nucleons and the total binding of the two frqgment nuclei is about $(8.35-7.5)235 \approx \approx 200$ mev.

Thus, the fission of a uranium nucleus liberates enormous energy -- on the order of 200 million electron volts. More precisely, the total fission energy is distributed as follows:

Kinetic energy of fission framents.............167 mev
Energy of fission gamma rays and fission framents.. 11 mev

The remaining portion is spread over a number of processes taking place in fission

In the process of nuclear fission, in place of the absorbed first neutron which produced the process, several secondary neutrons are formed. This can be explained as follows.

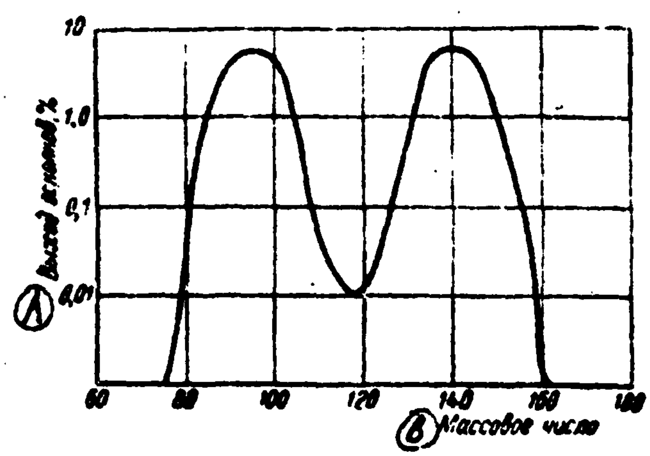

Figure 3. Yield of various fission fragments of uranium-235 upon its irradiation with thermal neutrons. A = Fragment yield, %; B = Mass number.

All of the fission fragments possess a higher ratio of neutrons to protons than is the case for stable, non-radioactive nuclei. The great majority of fragments are for this reason beta-active, however, in some of them the excess of neutrons is diminished by their emission. Neutrons emitted by nuclei are classed either as prompt neutrons or as delayed neutrons. Prompt neutrons are those which are emitted direcly in the fission process lasting 10^{-12} sec. An average of 2 or 3 prompt neutrons are emitted during a single fission event for uranium-235.

The relative number of such neutrons in certain energy intervals is given below:

Energy interval, mev	0—1	1—2	2—3	3—4	4—5	5—10	Over 10
Relative number of neutrons (per fission neutron) in given energy interval.................	0,308	0,294	0,186	0,103	0,055	0,052	0,0021
	1,00000						

In addition to the prompt neutrons immediately accompanying the act of fission, in a small number of cases (less than 1%) we also observe a phenomenon of neutron emission over a considerable time interval following fission. The sources of such neutrons, which have been called delayed neutrons, are certain of the fission fragments: e.g., Br^{87} or J^{137}. It is interesting to note that these isotopes emit neutrons with the same half-life that is characteristic of their beta activity (Fig 4).

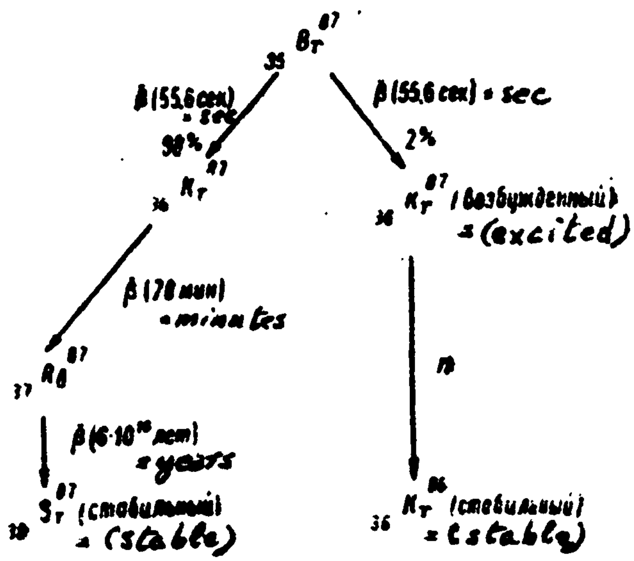

Figure 4. Decay scheme of $_{35}Br^{87}$ nucleus with emission of delayed neutron.

In Table 3 we present some data on delayed neutrons.

To conclude this section, let us briefly consider the problem of uranium nucleus splitting by neutrons of various energies. First of all we note that the secondary neutrons formed in fission can have the most diverse energies, up to and including 10-20 mev.

Neutorns with an energy of 0.025 ev are called thermal, while those over 0.5 mev are fast neutrons. Quite naturally,

the fission process requires some excitation energy E_{fis} (Fig 5) to overcome the so-called potential barrier [note: the potential barrier is a region of states of a material system with increased potential energy, separating regions of lower energies]. Thus, it will occur only under the condition that an amount of energy at least equal to E_{fis} is added to the system. In one case, it turns out that sufficient energy is provided by the binding energy which is released upon the addition of a thermal neutron to the nucleus; in the second case, a faster particle must be added. From the standpoint of industrial exploitation, the most feasible approach at the present time is thermal-neutron fission. Actually, uranium found in nature contains about 0.7% of U-235, traces of U-234, and over 99% U-238. Of the two uranium isotopes, only U-235 undergoes fission under bombardment by both fast and thermal neutrons.

Table 3

Delayed Neutrons Upon Fission of U-235 Under Bombardment by Thermal Neutrons

Период полураспада, сек. A	Энергия, кэв B	Относительный выход (от полного числа нейтронов деления), % C
55,6	250	0,025
20,0	570	0,166
4,51	412	0,213
1,52	670	0,241
0,43	400	0,085
		Полный выход: D 0,730

A = Half-life, seconds; B = Energy, kev; C = Relative yield (percentage of total number of fission neutrons); D = Total yield: 0.730.

U-238 undergoes fission only when bombarded by fast neutrons with an energy greater than 1 mev; with energies below 1 mev, the fission probability sharply falls off to zero. Fast neutrons are formed directly in the fission process, but already after several collisions with nuclei of surrounding matter or uranium itself they lose velocity and can no longer effect the fission of U-238. As a result, they become thermal and remain in this state until the moment of

capture now by U-235 nuclei in large measure. However, at the present time great strides are being made in the development of reactors using medium-energy and fast neutrons, in which the fission process takes place largely due to neutrons whose energies range from 0.1 to 0.5 mev and from 0.5 mev up.

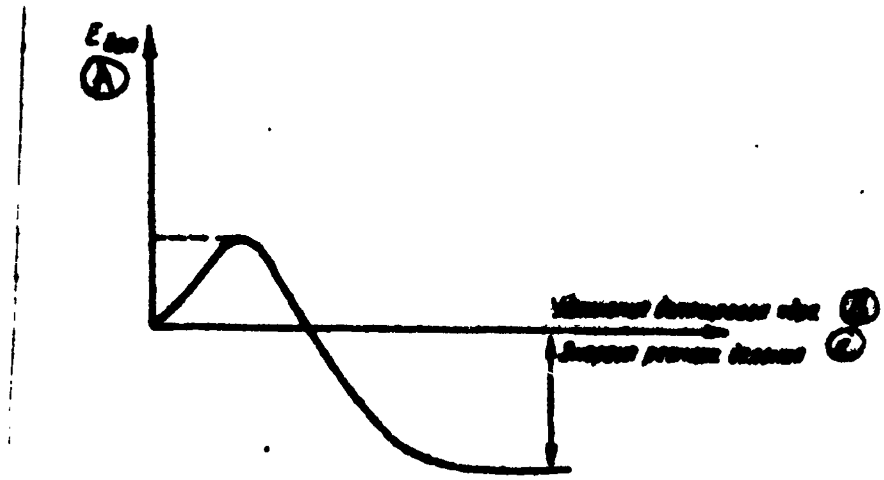

Figure 5. Qualitative representation of potential barrier which must be overcome in fission. A = E_{fis}; B = Elongation of splitting nucleus; C = Fission reaction energy.

The advantage of such reactors lies mainly in their substantially smaller size, which is of special importance in marine engineering.

5. The Chain Reaction and the Nuclear Reactor

As was pointed out above, nuclear fission is accompanied by the emission of secondary neutrons, whose number is greater than one. Let us assume for the sake of concreteness that two new neutrons are formed in fission (Fig 6) and each of them produces new fission events, i.e., the new nucleus has split to form two new neutrons which produce four neutrons, etc. This idealized case constitutes an idealized chain reaction. The name "chain reaction" is borrowed from chemistry where the term refers to a reaction whose products enter into combinations with the initial products, as a result of which the reaction develops continuously.

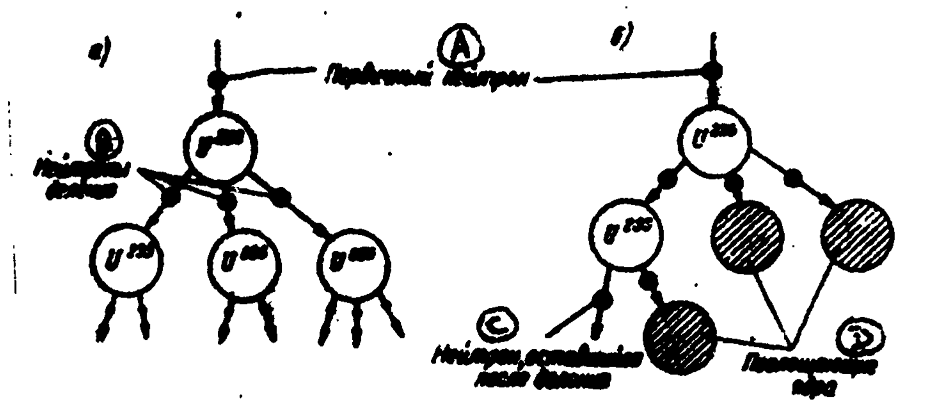

Figure 6. Comparison of chain reaction involved in uranium nucleus splitting with absorption (b) of some of the neutrons and without it (a). A = Primary neutron; B = Fission neutrons; C = Neutron remaining after fission; D = Absorption of nucleus.

The idealized case differs greatly from the actual one, however, inasmuch as there are several factors hindering the development of a chain reaction. Among these are:

1) the absorption of thermal neutrons by the fissionable material itself (e.g., radiation capture of neutrons by U-238) not accompanied by fission;

2) the presence of admixtures which absorb thermal neutrons in the uranium;

3) the leakage of neutrons from the reaction zone through the surface of the nuclear fuel. This process of neutron escape through the uranium surface without further fission has been termed neutron leakage;

4) fission occurs most effectively when realized by means of thermal neutrons; at the same time the majority of secondary neutrons have an energy of about 1-2 mev, so that it becomes necessary to slow them down by special means.

The latter fact is of decisive importance in the design of nuclear reactors.

In order to create favorable conditions for neutron retardation, it is necessary to mix the uranium with substances containing elements of low atomic weight which are capable of slowing down neutrons to thermal energies without their intensive absorption. The composition of the mixture (precentage content of moderator material and uranium) is carefully selected. If the proportion is properly determined, the number of secondary neutrons formed in such a mixture upon the completion of one fission cycle can exceed the number of primary neutrons by several percent, so that in such a system it is possible to have a self-maintaining or accelerating chain reaction.

The device in which a self-maintaining nuclear chain reaction takes place has been called a nuclear reactor. To realize the chain reaction it is necessary that the neutrons obtained in fission produce new fission events. When the volume of the mixture of the fissionable material and moderator is small, it is possible that a neutron will not collide with a single U-235 nucleus and will not produce a single fission event in passing through the volume. However, as the moderator-uranium mixture is increased the number of secondary neutrons, proportional to the reactor volume, rises more rapidly than their leakage, which is proportional to the reactor surface. For this reason, starting with a certain volume, the number of secondary neutrons begins to balance out the number of those absorbed, and a self-maintaining nuclear chain reaction becomes possible in the reactor. The amount of nuclear fuel corresponding to this volume has been called the critical mass.

To reduce the neutron leakage from the surface, the nuclear reactor is surrounded with a special neutron reflector [note: The reflector is a material which when hit by neutrons produces the elastic scattering of the latter back into the active zone. The most suitable materials for this purpose are dense substances of low atomic weight, e.g., beryllium, graphite, water, etc.]

The critical reactor size depends in the first place on the surface-volume ratio. For example, a sphere has the minimum ratio, so that a spherical reactor requires the least amount of nuclear fuel. Figs 7 and 8 are curves showing the relation of critical dimensions to mass.

To quantitatively evaluate the dimensions of the active zone of a reactor and determine the ratio of reactor power and fuel charge weight (mixture of U-238 and U-235) let us make use of the following formulas.

The critical reactor dimensions are found, as we have already established, as a function of its form according to the expressions:

$r = 3.14/F$ for a spherical shape;

$r = 2.945/F$ for a cylindrical shape, $(H = 5.441/F)$;

$a = 5.34/F$ for a cubical shape.

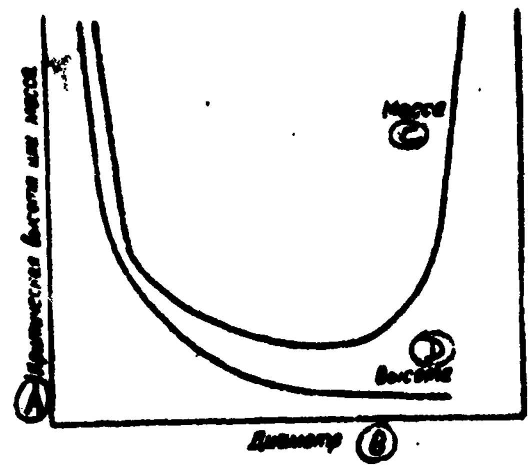

Figure 7. Dependence of critical mass of cylindrical reactors on the amounts of fuel and moderator. A = Critical height or mass; B = Diameter; C = Mass; D = Height.

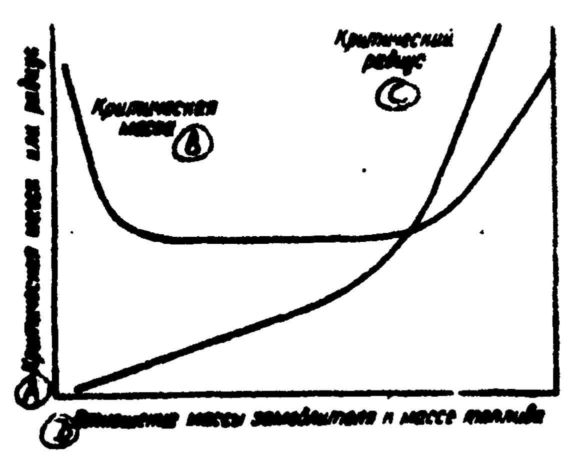

Figure 8. Dependence of critical mass of spherical reactor on its diameter. A = Critical mass or radius; B = Critical mass; C = Critical radius; D = Ratio of moderator mass to fuel mass.

Here r is the radius of the sphere or cylinder, H is the height of the cylinder, a is the side of a cube, and F is the so-called material Laplacian which depends on the breeding coefficient and neutron diffusion length [note: this is the distance in which the density of the neutron beam falls off by a factor of e].

For a reactor with a power on the order of 50,000 kwt and 144 heating units, researchers at Oak Ridge determined experimentally that $F = 8 \cdot 10^{-3}$ cm^{-1}.

Using the formula for a cubical reactor (its active zone), we obtain a cube size of $a = 5.84/8 \cdot 10^{-3} = 670$ cm.

The reactor charge is one the order of 800-1000 kg of U-238 in combination with U-235, provided there is a 5-7% enrichment of the indicated mixture with U-235 (i.e., the weight of pure uranium-235 will be about 40-70 kg).

A diagram of a nuclear reactor is shown in Fig 9.

The basic reactor elements are as follows:

the active zone -- the space in which the uranium

blocks and moderator are located; the nuclear fission reactions occur here;

the cooling system along which the primary heat transfer agent (water or other materials) circulates to remove heat from the cative zone; this is called the primary heat transfer loop;

special control elements.

Let us introduce the concept of the neutron breeding coefficient which will facilitate the explanation of reactor operation. The neutron breeding coefficient K is defined as the ratio of the number of neutrons formed in fission to the number of neutrons disappearing due to absorption or leakage, i.e.,

$$K = \frac{\text{number of neutrons formed in fission process}}{\text{number of neutron disappearance events}}.$$

In cases where the chain reaction begins with breeding coefficients somewhat in excess of unity ($K > 1$), the density of neutron streams (and therefore the reactor power) begins to increase gradually. When the reactor power has been brought up to the necessary level, the neutron breeding coefficient must be made to equal one. In htis case the number of neutrons and the amount of energy released per unit time will remain constant.

Reactor power is varied by means of control over the size of the thermal neutron stream. For this purpose, the reactor is equipped with control rods whose working portion containing isotopes is submerged in the active zone where it absorbs thermal neutrons (e.g., cadmium, boron). Upon submersion of the control rods into the active zone of an operating reactor, the breeding coefficient falls off and can be made to equal one or less due to additional absorption of thermal neutrons by these rods. As a result, reactor power becomes constant ($K = 1$) or drops off ($K < 1$).

When it reaches the required level, the control rods are once again returned to a position corresponding to $K = 1$, and the reactor continues to operate at reduced power. Increases in reactor power are realized analogously -- through the removal of the control rods from the active zone.

In addition to the control rods, each reactor is equipped with rods which compensate the reactor "poisoning" effect. This consists in the accumulation of fission fragments which absorb neutrons in the heat release elements (HRE). These rods quench excessive reactor reactivity, which is unnecessary in the initial stage of operation and is gradually reintroduced as reactor poisoning progresses. With respect to design and means of control, shim (compensating) rods need not differ from the control rods. For this reason, shim rods and control rods are referred to by the general term "control rods". [note: the quantity K-1 is the excess neutron

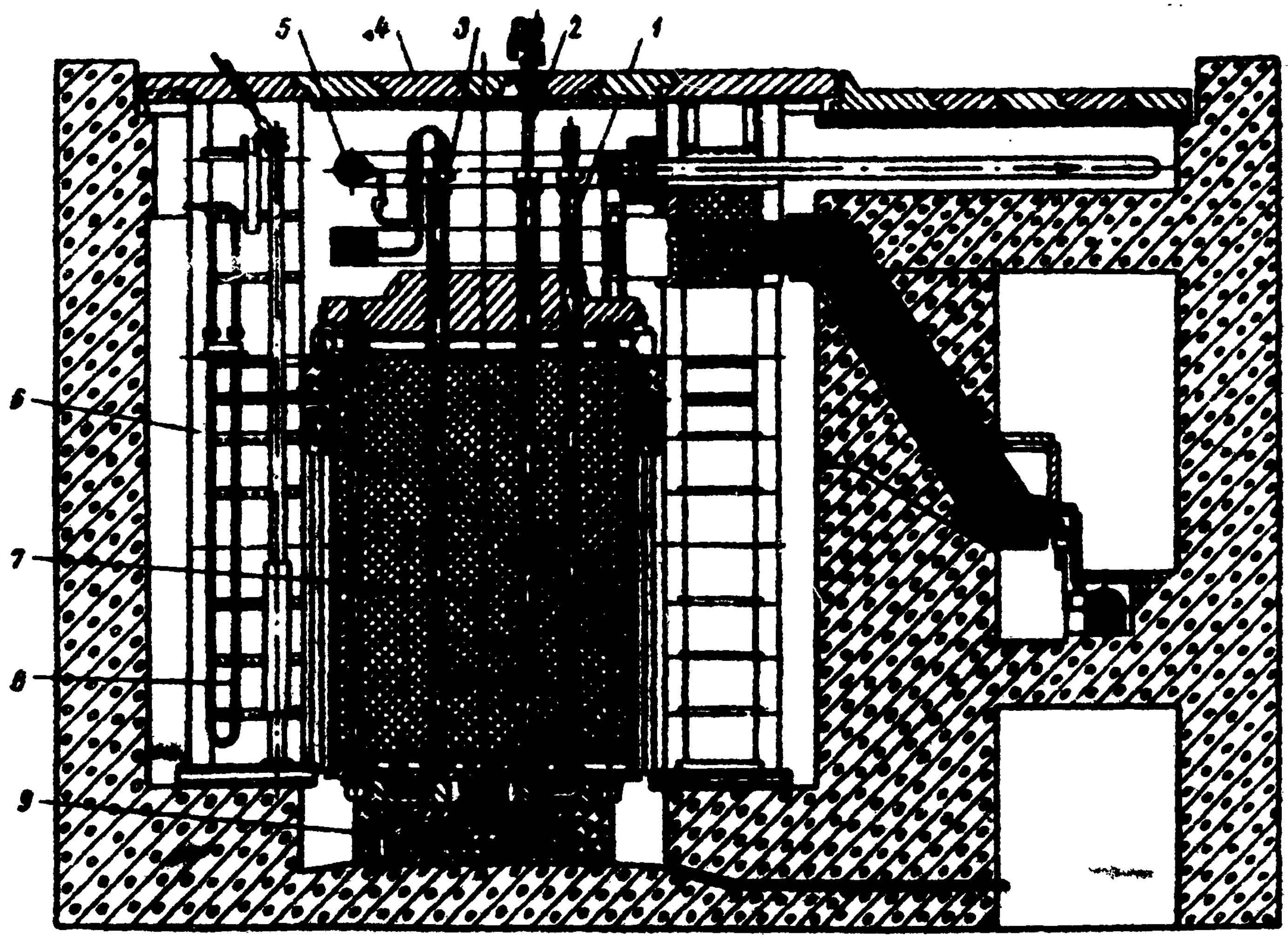

Figure 9. Simplified diagram of uranium reactor. 1 -- Automatic control channel; 2 -- Safety channel; 3 -- Hot channel; 4 -- Top shielding (cast iron); 5 -- Primary heat loop; 6 -- Side shielding (water); 7 -- Active zone; 8 and 9 -- coolers.

breeding coefficient, while the ratio (K-1)/K is the reactor reactivity.]

Generally speaking, the control rods can be broken down into three groups in accordance with their functions: emergency shut-down rods, shim rods and control rods as such.

The control rod, as was indicated above, is intended to maintain the specified power level constant. The rod is usually shifted automatically, but manual control can also be provided for.

Shim rods are used to compensate for "poisoning"of the reactor, for sharper and more significant variation of activity (than that of which the control rods are capable).

Emergency shutdown rods are intended for normal or emergency reactor shutdown and must move very quickly in the active zone. These rods are actuated automatically in the event of an emergency by means of various emergency signals. All of these types of rods are designated by the abbreviation CPR (control and protection rods).

However, there is a factor which facilitates the realization of a controlled chain reaction in uranium. As we already know, all neutrons are emitted simultaneously with the splitting of the uranium nucleus: about 1% of the neutrons are emitted by fission fragments with a considerable delay, which is sometimes as high as 50 sec. These delayed neutrons greatly retard the development of the chain reaction process for values of the breeding coefficient K close to unity.

Let us assume that we have brought K to unity. This implies that the loss of neutrons is totally compensated by the neutrons newly formed in fission. In this case the cahin process takes place due to the delayed neutrons, since without them the value of K is about 0.99. If we now increase K to 1.01, this will not occur immediately. Due to the prompt neutrons, the value of K will rapidly rise to unity. The delayed neutrons will be able to increase the value of the breeding coefficient no sooner than 50 sec, so that there will be a gradual development of the chain process. An analogous situation exists when K is reduced to values below unity.

Thus, varying K in the neighborhood of 1, we can effect the gradual acceleration or retardation of the fission process, and consequently regulate energy release in the reactor.

Classification of Reactors

Nuclear reactors are classed somewhat arbitrarily according to the following criteria:

1) the neutron energy -- the fission process can be brought about by thermal, fast, and medium-energy neutrons;

2) design of active zone -- so-called homogeneous and heterogeneous reactors;

A reactor in which the fuel and moderator constitute a single mixture in the form of a solution, alloy, chemical compound, or suspension is called a homogeneous reactor.

If the fuel is distributed in the form of spatially separated blocks surrounded by the moderator, then such a reactor is called heterogeneous;

3) the type of fissionable material employed. Reactors may use either natural uranium or uranium enriched with the U-235 isotope;

4) the nature of the moderator -- graphite, heavy water, ordinary water, etc;

5) the type of heat transfer agent -- water, gas, organic, or liquid-metal cooling;

6) purpose -- research, experimental, test, or power-production reactors.

Reactor Materials

In designing reactors within a given complex, in addition to the ordinary requirements with respect to the materials used -- anticorrosiveness, high strength, plasticity and good heat conduction, special attention must be paid to nuclear properties, depending on the actual purpose and design.

It is necessary to distinguish the following basic groups of materials:

1) fissionable materials;
2) retarding materials -- moderators;
3) coolants or heat transfer agents;
4) structural materials for pipes, coverings, and other elements in the active zone;
5) radiation shielding materials;
6) neutron absorbers (for controls);

Basic information on the most important materials employed in modern nuclear technology will be found in Table 4.

Table 4

Some Important Materials Used in Nuclear Technology

Nuclear fuel	Uranium-235, uranium-233, plutonium-239
Heat transfer agents	Air, helium, heavy or ordinary water, lead and bismuth, sodium
Moderators	Heavy or ordinary water, graphite, beryllium
Structural materials	Steel, aluminum, zirconium
Shielding materials	Water, concrete, steel, lead, boron

Among the fissionable materials used at the present time are U-235, plutonium-239, and certain other materials.

Moderators are usually materials of low atomic weight. One of the most important properties of moderators, of decisive importance in their selection is the ability to retard and absorb neutrons. It is desirable to have a moderator which absorbs fission neutrons minimally, but effectively lowers their energy down to a thermal level. For this purpose, for example, it is possible to use ordinary or heavy water. Ordinary water absorbs neutrons somewhat more intensively that heavy water and can be used as a moderator but only in reactors with an enriched fuel.

Heat transfer agents are materials having a high heat-transfer coefficient, low fission neutron absorptivity, low chemical aggressiveness, stability of physical properties upon heating and ionizing irradiation, absence of toxicity and flammability.

Practically no real substance fully satisfies all of these requirements. For this reason, a heat transfer agent is chosen with proper regard for concrete reactor operating conditions.

In low-power reactors, where the released heat is actually not used, air is a widely-employed coolant.

Natural and heavy water are widely used as heat-transfer agents. At the same time, they play the role of moderators in high-power reactors (ship power plants), due to their high heat transfer coefficients (100 times greater than of gases).

Other heat transfer agents are liquid metals -- lead, bismuth, sodium, and their alloys and oxides. As a rule, these are employed where very hgih temperatures and heat transfer coefficients are needed.

Among the most important structural materials are lead, beryllium, aluminum, stainless steel, zirconium, and a number of others. Such a choice is explained by their sufficiently high chemical stability and physical strength under high temperatures. The most important among them are certainly aluminum, zirconium, and stainless steel. Aluminum is employed in reactors with low heating temperatures; zirconium and stainless steel are used widely in high-temperature reactors.

The Nuclear Power Plant

In nuclear power plants the source of energy is the nuclear reactor 1. The energy it releases due to the fission process is converted into heat, which is then transformed into mechanical work or electricity (Fig 10).

The loop along which the heat transfer agent circulates is called the "primary technological loop". The heat transfer agent gives up its heat to a special working

fluid in heat exchanger 3; this fluid circulates in the so-called secondary technological loop.

The secondary loop operates a steam turbine or some other device (4). Both the first and second loops contain special circulation pumps 2 and 6 which continuously dirve the fluid or steam over the closed loop.

Part of the heat transfer agent passes into the special heat exchanger 5 where it is cooled by sea water and enters the system which cools the bearings of the circulating pumps, special filters, etc. The heat exchanger between the first and second loops is called the steam generator (3) as distinct from the heat exchangers performing the cooling functions.

The following basic types of nuclear power plants (NPP) are used to power nuclear vessels.

Water-cooled steam turbine plant. Such a plant requires high water pressure, which in turn makes it necessary that extra-high-strength materials be used. Installations of this type usually require enriched nuclear fuel.

Helium-cooled gas turbine plant. Its advantage consists in the fact that helium is non-reactive, and this makes it possible to reduce the total weight of shielding. High pressures in the heat exchange system are not a necessity. Its disadvantage is the low heat capacity of helium, which requires an increase in the size of the active zone and compressor power.

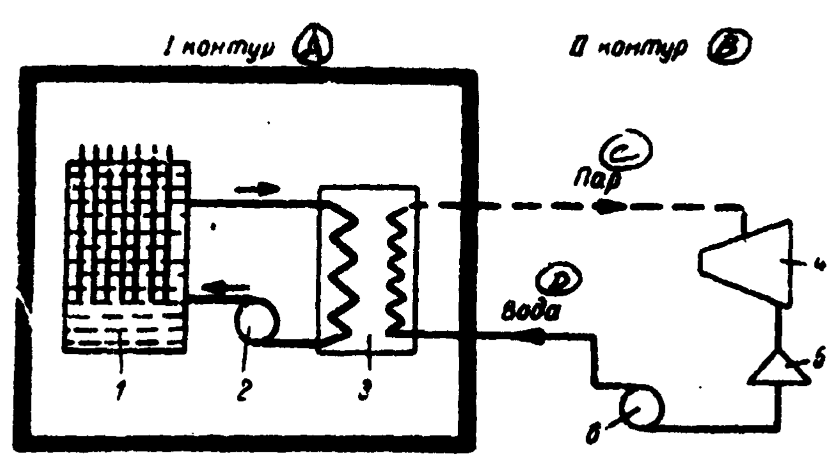

Figure 10. Diagram of nuclear power plant. A = Loop I; B = Loop II; C = Steam; D = Water.

Liquid-metal-cooled and steam turbine plant. The metallic heat tranfer agent possesses very high heat

capacity, and does not require relatively high temperatures and pressures. Its disadvantage is the high radioactivity of the primary loop (when sodium-potassium alloys are used).

Plant with organic heat transfer agent. This is conceivable in principle. There is insufficient information on this type of NPP available at the present time.

Plant of the so-called "boiling reactor" type. In such plants the nuclear fuel is used analogously to reactors with water under pressure, with the sole difference that the steam turbine receives steam formed directly in the active zone. This makes it possible to construct a very economical power reactor, which however requires the inclusion of the entire secondary loop in the zone of possible radioactive contamination.

At the present time, nuclear vessels are making wide use of water-cooled reactors. These have already been installed on nuclear submarines built by the US and Britain and the atomic icebreaker "Lenin"; the installation of reactors of this type is planned for planned ships of the US, Britain, Japan, Sweden, and other countries.

In connection with the fact that only reactors with water as the heat transfer agent are used in world ship design at present, this work will examine the problems of radiation safety only with reference to reactors of this type. However, it should be noted that there is great promise in the use in NPP of liquid-metal and organic heat transfer agents, which will make possible a considerable reduction in the dimensions and weight of power installations.

6. Ionizing Radiation from Nuclear Reactors

The sources of ionizing radiation in NPP are distinguished according to the type of reactor and the types of nuclear fuel employed, the heat transfer agent, and the moderator.

The peculiarity of the danger of ionizing radiation is related to the fact that humans lack sense organs which sould react to this type of radiation, so that the least amount of carelessness can lead to irreparable damage to the organism. Radioactivity formed in reactors is indeed enormous, while the amount required to inflict damage to health is very small. It is quite natural that measures to prevent the spread of contamination and radioactive materials must be observed very strictly.

As is known, nuclear fission in uranium blocks is accompanied by the formation of radioactive fragments and intensive gamma and neutron radiation. The fission fragments then decay, emitting beta particles and gamma quanta; they are therefore a great source of radioactive danger. For this reason, uranium blocks are enclosed in hermetic containers

which prevent the escape of fragments and their spread beyond the active reactor zone. It should be remembered that in the event of some violation of the wholeness of uranium block shells, the fission fragments (both solid and gaseous) will certainly enter the heat transfer agent. This will produce intensive contamination of the plumbing of the main circulation pumps and other primary-loop elements. There arises the danger of seepage from various joints, gaskets, packing, etc., which may lead to a contamination of enclosures and equipment.

All of this requires stringent control over the state of the radiation plant on the ship.

Neutron and Gamma Radiation in the Active Zone

Among all of the elements of an NPP, the active zone is the most powerful souce of ionizing radiation.

Reactor radiation consists of gamma quanta and neutrons. This includes prompt and delayed neutrons, spontaneous fission gamma rays, gamma rays from fission fragments, capture gamma rays of the nuclear fuel or heat transfer agent with the moderator, and a number of other forms of radiation which are of no great significance.

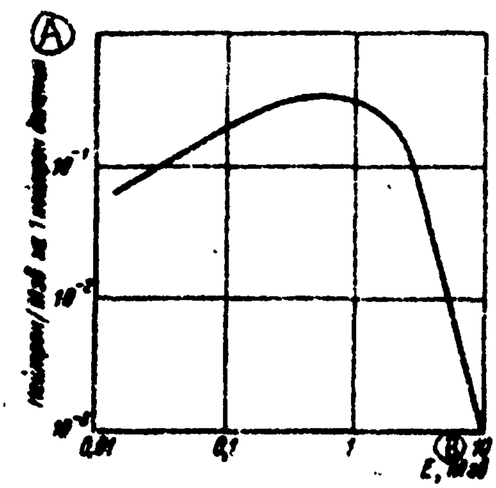

Figure 11. Energy spectrum of fission neutrons. A = Neutron/mev per fission neutron; B = E, mev.

Neutron radiation. Prompt neutrons are neutrons emitted at the moment of nuclear fission lasting 10^{-12} sec and making up over 99% of the total number of emitted neutrons. Delayed neutrons make up a negligible portion (e.g., 0.7% for uranium) of the total number of fission neutrons.

There are five distinct groups of delayed neutrons, classed according to the rate of decrease of their intensity (see Table 3).

From the standpoint of shielding, in view of their small proportion in the overall stream, the delayed neutrons can be neglected in comparison with the prompt ones. However, in the case of damage to the active zone structure, it is possible for the fission products to enter the heat transfer agent in the primary loop, as a result of which the latter becomes a source of delayed neutrons. Neutrons emitted directly during fission (prompt neutrons) have a significantly greater energy and intensity, and for this reason have the greatest effect on the structure of shielding from neutron radiation. The average energy of such neutrons is extremely high -- about 2 mev (Fig 11).

As an example which clearly shows the great danger of neutron streams in the event of insufficient shielding, let us consider a reactor with a thermal power of 800 thousand kwt. With such a power, the total size of the neutron stream is about $6 \cdot 10^{19}$ neutrons. This is easily seen if we take into account the fact that $7.8 \cdot 10^{10}$ neutrons are emitted in the production of 1 wt of energy per second. However, self-absorption of radiation within the reactor is great [see note] as a result of which only about 1-2% of the neutrons will reach the shielding material, i.e., about $6 \cdot 10^{17}$ neutrons. With an active zone surface of about 6 m^2, we obtain a value of about 10^{13} neutrons/cm^2sec for the neutron flow through the surface.

From a comparison of this value with the maximum permissible rate, having the following values for a daily 5-hour irradiation period: for fast neutrons 17 neutrons/cm^2sec, and for thermal neutrons 1500 neutrons/cm^2sec, we see the necessity for special protection for the operating personnel.

The <u>gamma radiation</u> from a nuclear reactor is classed as prompt gamma radiation, gamma radiation from the radioactive fission fragments, and gamma radiation from the induced activity in the moderator, heat transfer agent, reflector, and structural materials in the active zone.

Below we present some data on the energy spectrum of prompt gamma emission in uranium fission:

Energy interval, mev	0,25—0,75	0,75—1,25	1,25—1,75	1,75—2,25	2,25—3,25	3,25—4,25	4,25—5,75	5,75—6,75
Number of gamma quanta per fission event	3,1	1,9	0,84	0,55	0,2	0,062	0,02	0,007

Total of 7.0 quanta/event, 11 mev/event

The relative proportion of high-energy gamma radiation (so-called hard radiation, over 1-2 mev) is quite negligible.

In Table 5 we list some of the isotopes having hard gamma radiation.

The basic group of gamma quanta is the group with an energy of 0.75 mev, although we know that some gamma quanta are released with an energy of up to 7 mev.

It is necessary to deal briefly with so-called capture emission. It is formed at the moment of absorption of thermal neutrons by nuclei of the material in the active zone. This process in turn can lead to the appearance of radioactive nuclei and the subsequent emission of quanta through their decay.

Some data on gamma quanta emitted by means of capture radiation are presented in Table 6.

Table 5

Uranium Fission Fragments Emitting Hard Gamma Radiation

Изотоп (A)	Период (B) полураспада	Энергия гамма-(C) квантов, *Мэв*	Число гамма-квантов (D) на 10^4 распадов
Rh^{106}	30 сек = sec	2,9	1
Pr^{144}	17,5 мин = min	2,18; 2,6	11; 11
Eu^{156}	15,4 дня = days	2,0	1
La^{140}	40 час. = hours	2,5	20
J^{132}	2,4 часа = hours	2,0	12
Te^{131}	25 мин. = min	2,21	10
J^{134}	6,7 часа = hours	2,4; 1,8	11; 22
Rb^{88}	17,8 мин. = min	2,8; 1,86	46; 56

A = Isotope; B = Half-life; Gamma quantum energy, mev = C; D = Number of gamma quanta per 10^4 decay events.

Along with the aformentioned forms of radiation, there are also sources of emission whose sources are located outside the active zone.

We are referring to gamma radiation accompanying either the capture of thermal neutrons or the diffusion of fast neutrons in materials outside the reactor zone. In the first instance the basic contributing factor is gamma radiation accompanying the capture of neutrons in structural materials of the reactor body. The intensity of these sources depends on reactor power and the distribution of the thermal neutron stream. In the second instance gamma radiation is produced by induced activity in the reactor body and shielding. It is considerably less dangerous than direct radiation from

the active zone. However, this form of radiation should be taken into account, particularly following the shutdown of a nuclear power plant.

Table 6

Gamma Radiation due to Capture by Some Materials Used in Reactor Construction

Облучаемый материал (A)	Число γ-квантов на один захваченный нейтрон (B)	Энергия γ-квантов, Мэв (C)	Облучаемый материал (A)	Число γ-квантов на один захваченный нейтрон (B)	Энергия γ-квантов, Мэв (C)
Алюминий (D)	1,5	4,9	Кобальт (O)	0,9	5,3
Бериллий (E)	1,3	5,4	Медь (P)	0,9	6,2
Висмут (F)	1,0	4,2	Железо (Q)	1,1	6,4
Бор (G)	1,0	0,5	Водород (R)	1,0	2,2
Кадмий (H)	2,3	2,2	Свинец (S)	1,0	7,3
Кальций (I)	2,1	4,5	Магний (T)	2,1	3,9
Углерод (J)	1,3	3,5	Марганец (U)	0,8	5,7
Хром (K)	1,5	5,2	Калий (V)	1,2	4,4
Молибден (L)	1,1	4,6	Кремний (W)	3,9	3,9
Никель (M)	1,2	7,0	Натрий (X)	2,4	2,3
Азот (N)	1,7	6,1	Бетон (Y)	1,0	6,0

A = Irradiated material; B = Number of gamma quanta per captured neutron; C = Gamma quantum energy, mev; D = Aluminum; E = Beryllium; F = Bismuth; G = Boron; H = Cadmium; I = Calcium; J = Carbon; K = Chromium; L = Molybdenum; M = Nickel; N = Nitrogen; O = Cobalt; P = Copper; Q = Iron; R = Hydrogen; S = Lead; T = Magnesium; U = Manganese; V = Potassium; W = Silicon; X = Sodium; Y = Concrete.

Usually gamma radiation of this type is the result of the activation of stainless steel widely used in reactor construction. Some data on activation are given in Table 7.

In order to obtain a clear picture of the intensity of gamma radiation of a nuclear reactor, let us turn to the above example of the operation of a reactor with a thermal power of about 80 thousand [sic: example on p 33 (p 34 of source) reads 800 thousand] kwt. Over a period of several months of operation at full power, it produces several million curies of gamma activity. However, the percentage of the total gamma ray stream reaching the shielding will depend on the physical dimensions and structure of the reactor. The order of magnitude of the gamma ray stream at the edge of the active zone is about 10^{13} quanta/cm^{2}sec (taking

into account self-absorption in the active zone). Its comparison with the maximum permissible stream for an 8-hour irradiation period, equal to $0.7 \cdot 10^3$ quanta/cm^{2}sec with a mean quantum energy of 1.5 mev (which corresponds to 0.017 roentgen), gives a clear indication of the necessity of using particularly powerful protection against gamma radiation with compulsory control of the dosage beyond shielding limits.

Table 7

Induced Activity of Basic Components of Stainless Steel Upon Irradiation With Thermal Neutrons

Реакция (A)	Период полураспада (B)	Активность при насыщении, в числе распадов/см³·сек (C)	γ-активность при насыщении, квант/см³·сек (D)	Энергия квантов, Мэв (E)
$Mn^{55} (n, \gamma) Mn^{56}$	2,6 часа	$2,3 \cdot 10^{-2}$	$2,3 \cdot 10^{-2}$	0,845
			$5,7 \cdot 10^{-3}$	1,81
			$3,4 \cdot 10^{-3}$	2,13
$Cr^{50} (n, \gamma) Cr^{51}$	26,5 дня	$6,8 \cdot 10^{-3}$	$1,4 \cdot 10^{-4}$	0,32
$Fe^{58} (n, \gamma) Fe^{59}$	46 дн.	$4,8 \cdot 10^{-5}$	$2,4 \cdot 10^{-5}$	1,1
$Ta^{181} (n, \gamma) Ta^{182}$	117 дн.	$1,0 \cdot 10^{-4}$	$1,5 \cdot 10^{-4}$	1,13
$Co^{59} (n, \gamma) Co^{60}$	5,2 года	$5,6 \cdot 10^{-4}$	$5,6 \cdot 10^{-4}$	1,33
			$5,6 \cdot 10^{-4}$	1,17

A = Reaction; B = Half-life; C = Activity upon saturation, in number of decay events/cm^{3}sec; D = γ-activity upon saturation, quanta/cm^{3}sec; E= Quantum energy, mev.

From the above considerations we see that in the operation of the nuclear reactor, the most important role is played by the prompt neutrons of nuclear fuel combustion as well as the gamma radiation, both accompanying fission and arising as a result of thermal neutron capture.

The basic sources of radiation following reactor shutdown are gamma radiation of fission products, and gamma radiation due to activity induced in materials. For purposes of clarity, we have compiled summary Table 8 containing data on radiation from a hypothetical nuclear reactor during operation or shutdown periods, when a given type of radiation predominates. The Table does not require additional explanation.

Table 8

Radiation from Active Zone of a Hypothetical Power Reactor, Water Cooled, With Zirconium as the Structural Material

Вид излучения A	Происхождение излучения B	Энергия, *Мэв* C	Мощность источника D	Примечания
Нейтроны F	Деление K	ир to до 15	3,7·10^{13} *нейтр/см²сек* Q	Основной источник нейтронов при работе реактора S
»	Фотонейтроны L	» 15	5·10^{8} *нейтр/см²сек*	Основной источник спустя несколько минут после остановки реактора T
γ-кванты G	Мгновенное γ-излучение при делении M	» 7	3·10^{13} *квант/см²·сек*	Основной источник γ-квантов, испускаемых активной зоной при работе реактора U
То же H	Запаздывающее γ-излучение осколков деления N	0,1—3	1,0·10^{13} *квант/см²сек* J	Основной источник в активной зоне остановленного реактора V
» »	γ-излучение при захвате нейтронов в цирконии O	1—8	2,8·10^{10} *квант/см²сек* J	
» »	γ-излучение неупругого рассеяния нейтронов в цирконии P	1—8	1,5·10^{11} *квант/см²сек* J	
» »	γ-излучение при захвате нейтронов ядрами урана, ксенона, кадмия и серебра Q	1—8	2,3·10^{11} *квант/см²сек* J 7,5·10^{10} *квант/см²сек* J 4,5·10^{9} *квант/см²сек* J	
» »	γ-излучение при захвате нейтронов ядрами водорода воды R	2,2	5,5·10^{11} *квант/см²сек* J	

[Legend on following page]

Table 8: Legend.
A = Type of radiation; B = Source of radiation; C = Energy, mev; D = Source intensity; E = Remarks; F = Neutrons; G = γ -quanta; H = Ditto; I = Neutrons/cm^{3}sec; J = Quanta/cm^{3}sec; K = Fission; L = Photoneutrons; M = Prompt γ-emission with fission; N = Delayed γ-emission of fission fragments; O = γ-emission in neutron capture by zirconium; P = γ - emission from inelastic neutron scattering in zirconium; Q = γ - emission from neutron capture by uranium, xenon, cadmium, and silver nuclei; R = γ-emission from neutron capture by water hydrogen nuclei; S = Basic source of neutrons in reactor operation; T = Basic source of neutrons several minutes following reactor shutdown; U = Basic source of -quanta emitted from active zone during reactor operation; V = Basic source in active zone of banked reactor.

Ionizing Radiation From Technological Loops in a NPP

It was pointed out above that it is possible to use water, certain low-melting metals and their alloys, gases, and a number of organic compounds in NPP as heat transfer agents. Under certain conditions all of these NPP heat transfer agents do or are able to become radioactive. The causes of their induced radioactivity can be the following:

absorption of fission neutrons by the agent itself;

activation of substances arising in corrosion of structural materials used in the loops and which enter the heat transfer agent;

entry into the agent of fission fragments as a result of the disruption of the hermetic seal of the heating element shells.

Activity in loop containing water under pressure. The heat transfer agent must in the first place possess the properties which assure the removal of heat from the active zone. Water in particular happens to have satisfactory heat-transfer properties and a relatively low activation cross-section.

In designing it is taken into account that the heat transfer agent must be under a pressure such as would prevent any excess over the temperature corresponding to the boiling of water at the given pressure. In the contrary case, steam will form around the heating element due to the h gh temperature of the active zone surface; this can lead to a sharp decrease in heat transfer, overheating of the element, disruption of the hermetic seals of the heating element shells, and even the melting of the nuclear fuel.

To attain the necessary temperatures on the order of 300°C, it is necessary to provide high pressures (many tens of atmospheres). This imposes rigid requirements on loop design.

A water-cooled ship reactor is about 1-2 m in diameter, with a water pressure over 100 kg/cm^2 and a temperature of about 300°C (about 80 megawatts in power).

Under the action of neutron streams there is an activation of the water and the admixtures in it which are present even if the water is subjected to double distillation. The water becomes radioactive even in the absence of admixtures as a result of (n,p) reactions of the oxygen isotopes

$$O^{16}(n,p)N^{16} \text{ and } O^{17}(n,p)N^{17}.$$

The decay of isotope N^{16} which occurs with a small half-life (7.35 sec) is accompanied by the emission of extremely rigid gamma quanta (7.5 and 6.1 mev). The half-life of another radioactive nitrogen isotope (N^{17}) is equal to 4.14 sec; this is accompanied by the emission of beta particles with a maximum energy of 3.7 mev and neutrons with an energy of 1 mev. Despite their short half-life, these emissions greatly complicate the servicing of the primary heat transfer loop. Less important sources of radiation are the reactions

$$O^{18}(n, \gamma)O^{19}, \quad H^1(n, \gamma)H^2.$$

The probability of such reactions is small, and they are usually disregarded in calculating biological shielding for NPP.

Some information on the activation of various heat transfer agents is given in Table 9.

Table 9

Some Radioactive Isotopes Formed in the Activation of the Heat Transfer Agent and Its Admixtures

Теплоноситель A	Реакция B	Период полураспада C	Энергия излучения, Мэв D
Воздух E	$Ar^{40}(n, \gamma)Ar^{41}$	1,8 часа = hours	1,25 (β)
Обычная и тяжелая вода F	$O^{16}(n, p)N^{16}$	7,35 сек. = sec	7,1 (γ); 10 (β)
	$O^{17}(n, p)N^{17}$	4,14 сек. = sec	1n 3,7β
	$O^{18}(n, \gamma)O^{19}$	29,4 сек. = sec	4,5 (β); 1,6 (γ)
Натрий G	$Na^{23}(n, \gamma)Na^{24}$	14,8 часа = hours	2,76 (γ)
Вода с примесями H	$Al^{27}(n, \alpha)Na^{24}$	14,8 часа = hours	то же = ditto
	$Al^{27}(n, \gamma)Al^{28}$	2,4 мин. = min	—
	$Mn^{55}(n, \gamma)Mn^{56}$	2,6 час. = hours	0,845 (γ); 1,81 (γ); 2,13 (γ)
	$Fe^{58}(n, \gamma)Fe^{59}$	46 дн. = days	1,1 (γ); 1,3 (γ)

A = Heat transfer agent; B = Reaction; C = Half-life; D = Radiation energy, mev; E = Air; F = Ordinary and heavy water; G = Sodium; H = Water with admixtures.

Along with the induced activity of the heat transfer agent, the qctivated admixtures present in the water constitute an additional source of radiation which can be neglected. Actually, for water for example, the ratio of its own induced activity to that of the irradiated admixtures is about 300.

The water employed for reactor cooling contains about $0.5 \cdot 10^{-4}\%$ admixtures (by weight), which is the practical limit of modern purification methods. Only a bidistillate can satisfy such conditions. For the sake of comparison we might point out that ordinary drinking water contains up to $1 \cdot 10^{-2}\%$ impurities, while water in ordinary boiler systems -- from $2.5 \cdot 10^{-3}$ to $2.5 \cdot 10^{-2}\%$.

Table 10

Radioactive Isotopes and Water Heat Transfer Agent Admixtures

Изотоп A	Период распада B	Удельная активность C	Источник D
N^{16}	7,3 сек = sec	10^{-1} кюри/л E	O^{16} G H_2O
N^{17}	4,1 сек. = sec	800 нейтр/см²сек F	O^{17} G H_2O
K^{38}	7,7 мин. = min	$5 \cdot 10^{-5}$ кюри/л E	
Ar^{41}	1,8 часа = hours	$4 \cdot 10^{-5}$ кюри/л E	H Воздух в H_2O
F^{18}	1,9 часа = hours	$4 \cdot 10^{-5}$ кюри/л E	
Mn^{56}	2,6 часа = hours	$0{,}5 \cdot 10^{-5}$ кюри/л E	I Сталь
Na^{24}	14,8 час. = hours	10^{-6} кюри/л E	J Натрий в воде
Co^{60}	5,2 года = years	$2{,}5 \cdot 10^{-8}$ кюри/л E	I Сталь
Fe^{59}	46 дн. = days	$1{,}1 \cdot 10^{-8}$ кюри/л E	»
Ta^{182}	117 дн. = days	$0{,}6 \cdot 10^{-8}$ кюри/л E	»

A = Isotope; B = Decay time; C = Specific activity; D = Source; E = curie/liter; F = neutrons/cm³sec; G = in; H = Air in H_2O; I = Steel; J = Sodium in water.

The corrosion products formed as a result of chemical reactions of the heat transfer agent with the material of the technological loops are activated upon their irradiation with a powerful stream of neutrons during the passage of the heat transfer agent over the active zone. For sturctures usually made of stainless steel, the basic portion of the total activity is contributed by the activity of manganese-56 with a short half-life (2.6 hours). The proportion of long-living isotopes, such as cobalt-60 (5.2 years) and iron-56 (46 days) is not large. As was shown by a preliminary estimate carried out for the atomic icebreaker "Lenin", the activity of cor-

rosion products in the primary heat transfer agent -- the bidistillate -- makes up no more than 10^{-4} curie/liter; 80% of the activity is due to the decay of manganese-56 nuclei, while the remaining 20% is due to the decay of iron-59, cobalt-60, chromium-51, and nickel-65 nuclei. In this estimate it was assumed that the structural materials are corroded homogeneously and evenly, while the chemical elements in the corrosion products are in the same ratio as in the structural material. Some data on the isotope composition of heat transfer agent admixtures are given in Table 10.

The basic gas activity of the primary heat transfer agent (water) provided the heating elements are hermetically sealed will be due to the argon in the air found not only in the water itself, but also in the cooling system after it is filled with water, as well as the gases of fragment origin -- due to the surface contamination of the heating elements with uranium.

Radioactive gases can create a danger with gas seepage both from the primary and secondary technological loops of a NPP.

The activity of the heat transfer agent at the reactor oulet according to calculations carried out for the NPP of the "Lenin" is 0.18 curie/liter due to gamma radiation, $10^{-3} \div 10^{-4}$ curie/liter due to gas activity, and about 500 neutrons/cm^2sec due to neutron streams.

Radioactive gases and aerosols. Even under normal conditions of NPP operation, insignificant amounts of radioactive gases and aerosols are still formed in the immediate neighborhood of the reactor. The gas and aerosol activity arise both as a result of heat transfer agent evaporation in the presence of and uncontrollable minute seepage and of air activation.

For example, the design of the graphite reactor at Oak Ridge (US) features 30-cm spaces in the upper portion between the graphite neutron reflector and the concrete shielding in order to prevent thermal damage to the shielding. In these spaces there was intensive activation of argon in the air with the appearance of gas activity of about 0.5 curie of argon-41 per hour.

An analogous picture holds true with the reactor for physical and thermal experimentation of the Academy of Sciences USSR, in which about 4 curies of activity appear between the hermetic steel shell and the concrete shielding each hour.

Radioactive aerosols are formed largely due to the seepage from the primary technological loop of both the primary heat transfer agent itself and the volatile fission fragments (krypton, xenon, bromine, etc.) contained in it which then decay with the formation of radioactive aerosols.

For this reason, in designing technological loop elements -- piping, fittings, and mechanisms -- it is necessary to reduce all joints, including welded ones, to a minimum. At the same time, a small unavoidable leakage with a normal NPP operating regime does not as usual constitute a serious danger (see Chapters V and VII). Other forms of leakage capable of arising as a result of the disruption of the hermetic seal of the loops or steam generators are best classed as characteristics of a hazardous operating regime. They are considered in the appropriate section.

Explosive danger of a ship NPP. In conclusion it is necessary to consider the possibility of NPP explosion. It is known that the present heterogeneous reactors run on nuclear fuel which is also used in modern nuclear weapons.

However, one should not draw parallels between a uranium power reactor and the atomic bomb. In order for the bomb to explode, it must incorporate a large excess criticality ($K > 1.2$).

In order to accelerate the chain process it is necessary for it to be capable of developing in a time so short that the fuel (uranium) molecules have no time to come apart, thus reducing the critical mass. Thus, an enormous amount of energy is released in a very short time and an explosion occurs.

In contrast to this, the supercriticality of a reactor is small ($K < 1.075$, i.e., no higher than the amount of delayed neutrons -- 0.75% of the total stream). In addition, ship reactors have a special emergency protection system which is actuated in case the reactor power begins to increase too rapidly as a result of certain faults in the regulation and control apparatus.

But even if the reactor should go out of control, and an uncontrolled nuclear reaction does begin, as a result of the slow rate of increase of the energy released in uranium fission, the fuel molecules will have time to dissociate (lowering the critical mass) and the energy required for an explosion is not accumulated. At the same time, a water-cooled heterogeneous reactor experiences a water boilout which shifts the neutron balance, and the chain reaction is quenched.

The above factors reduce the possibility of a reactor explosion practically down to zero.

Chapter III

PRINCIPLES OF SHIP NUCLEAR POWER PLANT (NPP) SHIELDING

7. Protection From NPP Radiation

The problems of protection against radiation from a nuclear power plant are complex and varied in general, and particlularly so under ship conditions. On the one hand, it is necessary to afford reliable protection to the personnel from ionizing radiation, and on the other, the construction of shielding must leave at least partial access to individual NPP communications, mechanisms, and apparatus. The basic task with which we deal in calculating shielding for a ship NPP is the assurance of its reliability with minimal size and weight.

The design of shielding is determined basically by the properties and nature of the radiation and the necessary degree of its weakening. The latter can be determined on the basis of the initial intensity and the maximum permissible radiation level at variou points beyond the shielding

The following factors must be taken into account in selecting and calculating the proper shielding:

1) the energies of penetrating radiation;

2) distribution of radiation in the direction of ship living and service quarters;

3) geometry of NPP radiation sources.

From the standpoint of protection from gamma rays, the most effective shielding is afforded by heavy elements with a high atomic number; such materials are not very effective in weakening fast neutrons, however. In view of the fact that the neutron capture cross-section increases rapidly with their reduction down to a thermal energy level, improved neutron shielding requires that it be made of light elements fulfilling the role of moderators, along with heavy ones. The shielding can be made up of successive layers of heavy and light elements or in the form of a homogeneous mixture of these elements.

Neutron capture is accompanied by gamma radiation. This complicates the problem of neutron shielding, since for

isotopes the gamma radiation due to capture is characterized by fairly high energy ranging approximately from 7 to 10 mev.

The requirements imposed on NPP shielding are to a considerable degree determined not only by the active zone of the reactor itself, but also by other portions of the primary technological loop -- the pumps, heat exchangers, pipes, etc.

There are two types of NPP radiation shielding -- primary and secondary.

Primary shielding not only weakens the neutron stream to a point at which gamma radiation accompanying neutron capture in the shielding is down to a minimum together with the activation of the secondary heat transfer agent and structural elements of the NPP beyond the primary shielding, but also affords protection from thermal effects of the active zone on the radiation shielding structures.

Shielding lowers the intensity of penetrating radiation down to maximum permissible levels and serves as a barrier to the penetration of radioactive gases and aerosols into ship enclosures.

Let us consider some of the problems of shielding calculation.

In calculating gamma-ray shielding, we make use of the exponential attenuation law

$$I = I_0 e^{-\mu x}, \tag{2}$$

where I_0 is the intensity of primary radiation;

μ is the attenuation coefficient for the shielding material;

x is the thickness of the shielding layer.

However, this formula takes into account only the change in the intensity of the direct (primary) radiation in a narrow beam. It is assumed that any interaction of a gamma quantum with the medium removes it from the beam. In the attenuation of broad gamma-ray beams such as takes place in actual NPP shielding, along with direct gamma radiation we observe a dispersed gamma component which will of course increase the size of the radiation dose penetrating the shielding in comparison with that of the dose given by formula (2).

To take into account dispersed radiation in the calculation of thick protective layers, the coefficient B, called the buildup factor, is introduced into formula (2); then

$$I = I_0 B e^{-\mu x}. \tag{3}$$

Obviously, B 1 and depends on the nature and thickness of the shielding, as well as on the initial gamma energy. As gamma energy increases, B falls off for most materials; it increases with thickness regardless of material.

The numerical value of B for almost all substances except lead and other heavy elements can be determined approximately on the basis of the relations

$$B = 1.2\ \mu x \quad \text{for} \quad E = 2 \text{ mev}$$
$$B = 0.8\ \mu x \quad " \quad E = 3 \ "$$
$$B = 0.5\ \mu x \quad " \quad E = 10 \ "$$

For lead, $B = 0.5\mu x$ in the energy interval $E = 1 \div 3$ mev.

Let us estimate roughly the intensity of gamma radiation emitted by the active reactor zone beyond the shielding. From the balance or energy released in a single fission event it follows that the total energy of the gamma radiation is about 5 mev per event. The total energy released in fission is 199 mev. Thus, the energy of the gamma radiation is about 5-6% of the total energy released in fission. Assuming that about 90-95% of the gamma-ray energy is absorbed in the active zone, it is possible to make an estimate of the size of the quantum stream released from the active zone with an average gamma-quantum energy of $E = 2$ mev according to the formula

$$I = 0.3 \cdot 10^{14} Q,$$

where Q is the thermal reactor power in kwt.

If the active zone has a cylindrical shape with an optimal ratio of height H to diameter D ($H = 0.92$ D), its surface $S = 5.5V^{2/3}$ where V is the volume of the active zone.

Consequently, the initial gamma stream is

$$I_o = I/S = 5.45 \cdot 10^{12} QV^{-2/3}. \qquad (4)$$

Substituting (4) into formula (3), it is possible to estimate the shielding thickness required to lower radiation intensity down to the maximum permissible level.

For thick shielding it is likewise necessary to take into account attenuation due to distance according to an inverse-square law. Thus, for an active zone of diameter d surrounded by shielding of thickness h, the formula which defines the attenuation of radiation from the active zone is:

$$I = I_o B e^{-\mu x}[d/(d+h)]^2. \qquad (5)$$

Here x varies from zero to h, and I_o is the gamma stream at the boundary of the active zone.

The calculation of neutron shielding is complicated by the fact that for fast neutrons the basic form of interaction with nuclei is elastic and inelastic scattering. This leads to the accumulation of neutrons in the shielding whose number raches a maximum for a certain thickness and then falls off due to thermal neutron absorption.

The mean-square distance at which the fast neutrons are slowed down can be determined from the ratio between the mean square of the distance at which the neutrons become thermal, and the retardation distance L:

$$\bar{R}^2 = 6L^2. \qquad (6)$$

For water $L^2 = 33$, consequently, the mean-square distance $R = 14$ cm. For graphite ($L = 300$) this distance is 42 cm. From these examples we see that water shielding from fast neutrons is more effective than graphite shielding.

After the neutrons become thermal, they can pass in the shielding for great distances by diffusion before being absorbed, so that the value of R from formula (6) does not determine the thickness of shielding sufficient for a prespecified neutron attenuation.

To determine the average distance traveled by a fast neutron from the point of its origin to the point of absorption, it is necessary to add the mean square distance over which the neutrons diffuse after being slowed down to a thermal level to the mean-square distance traveled by neutrons in the attenuation process.

The numerical values of the attenuation and diffusion distances for some materials will be found in Table 11.

Table 11

Numerical Values for Attenuation and Diffusion Distances for Some Materials

Замедлитель (A)	Плотность, г/см³ (B)	Длина замедления, см (C)	Длина диффузии, см (D)
Тяжелая вода (E)	1,1	11	100
Углерод (графит) (F)	1,62	18,7	50,2
Бериллий (G)	1,84	9,9	23,6
Вода H_2O (H)	1	5,7	2,88

A = Moderator; B = Density, g/cm^3; C = Attenuation distance, cm; D = Diffusion distance, cm; E = Heavy water; F = Carbon (graphite); G = Beryllium; H = Water H_2O.

For approximate estimates of neutron reactor shielding we can take the exponential law for fast-neutron attenuation:

$$n = n_0 e^{-x/\lambda_p}, \qquad (7)$$

where λ_p is the so-called relaxation distance equal to the thickness of the material in which the fast-neutron stream is weakened by a factor of e ($e \approx 2.72$).

The values of λ_p for some shielding materials for fast-neutron energies of 6-8 mev are given in Table 12.

Table 12

Values of Relaxation Distances for Fast (6-8 mev) Neutrons for Certain Shielding Materials

Материал защиты A	Плотность, г/см³ B	λ_p, см C
Графит D	1,7	14,4
Бетон E	2,3	11,1
Вода F	1	10,3
Свинец G	11,3	8,8

A = Shielding material; B = Density, g/cm^3; C = λ_p, cm; D = Graphite; E = Concrete; F = Water; G = Lead.

As an example we shall calculate the thickness of concrete required to lower the fast-neutron stream from 10^{11} fast neutrons/cm^{2}sec to the maximum permissible value of 17 fast neutrons/cm^{2}sec.

Solving equation (7) with respect x, we have

$$x = \lambda_p \ln(n_o/n).$$

From Table 12 we find that for concrete $\lambda_p = 11.1$; thus,

$$x = 11.1 \ln(10^{11}/20) \approx 250 \text{ cm}$$

The problem of shielding out thermal neutrons is looked upon differently, since the character of their scattering differs considerably from that of fast neutrons and gamma rays.

The value of the initial flow of thermal neutrons from a flat source at a distance r is calculated from the formula

$$n = n_o e^{-r/l}, \tag{8}$$

where l is the diffusion distance [see note] (l = 2.88 cm for water). [Note: The diffusion distance is the length over which the neutron density is reduced by a factor of e (becuase of this l is also sometimes called the relaxation distance)].

In designing shielding it is likewise necessary to bear in mind the evaluation of the heating effect resulting from the absorption of radiation in the NPP structures, including the reactor body shell. Upon absorption of gamma quanta and neutrons their energy is converted into heat, so that the shielding heats up. The presence of heat liberation makes desirable the use of a material with high heat conductivity as shielding. In the contrary case, thermal expansion can lead to great mechanical stresses, and consequently to damage of shielding structures. Concrete, a widely used shielding material, requires special cooling techniques because of its low heat conductivity; otherwise, it will begin to lose its hydrogen which plays a basic role in the retardation of fast neutrons. Its temperature must be kept below 200°C. In connection with the fact that shielding materials mostly have considerable thermal expansion coefficients, there must be special thermal shielding of the reactor and biological shielding structures from heat produced in the active zone.

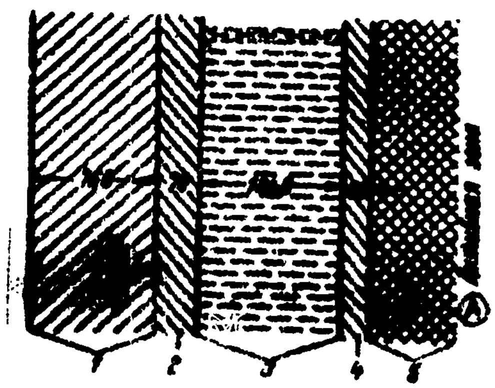

Figure 12. Shielding of atomic passenger-cargo vessel "Savannah" to be built by the US. 1 -- Barite concrete; 2 -- Steel; 3 -- Water; 4 -- Thermal shielding (steel); 5 -- Graphite reflector; A = Active zone.

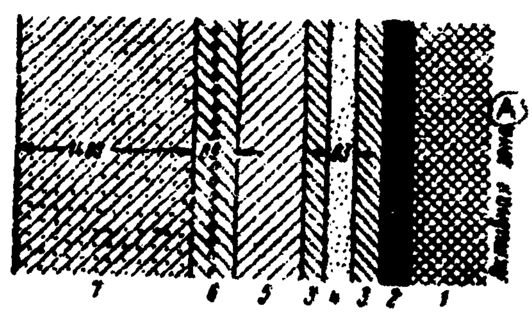

Figure 13. Shielding of the SR-5 experimental reactor (US) with a thermal power of 4000 kwt. 1 -- graphite reflector; 2 -- lead poured into interstices; 3 -- aluminum jacket; 4 -- boral carbide; 5 -- steel reactor tank; 6 -- lead blocks with cooling coils; 7 -- concrete; A = Active zone.

A convenient form of shielding are steel plates immersed in water for cooling or a thin steel sheet in the form or a cylinder cooled by water in special cooling coils.

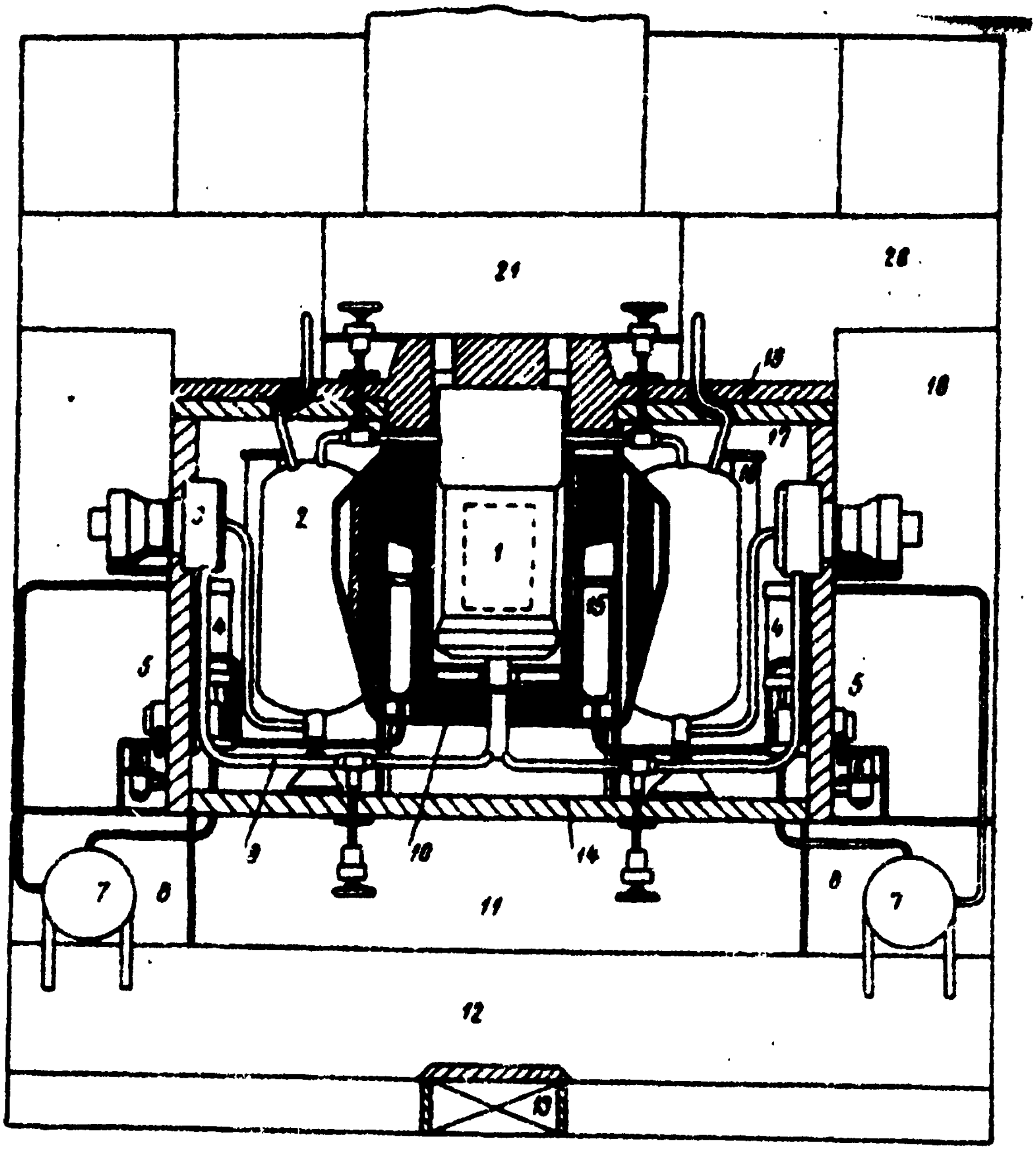

Figure 14. Cross-sectional view of central cubicle of the atomic icebreaker "Lenin". [See legend next page].

To lower gamma radiation due to capture, lithium or boron are added to the water coolant.

The simplest and easily-designed radiation shielding is a large water basin in which the reactor and its thermal shielding are immersed.

Neutrons are absorbed by water more quickly than gamma rays, and the required thicknesses of the water layer are determined by the gamma radiation passing through the thermal shielding.

Figure 14. Legend.
1 -- Reactor; 2 -- Steam generator; 3 -- Main circulation pump; 4 -- Filter refrigerator; 5 -- Emergency circulation pump; 6 -- Inner-loop circulation pump; 7 -- Outer-loop refrigerator; 8 -- Outer-loop refrigerator compartment; 9 -- Primary-loop pipes; 10 -- Iron-water shielding tank; 11 -- Heat control pickup compartment; 12 -- Ship pump compartment; 13 -- Cistern for radioactive water from the primary loop; 14 -- Steel shielding; 15 -- Filter; 16 -- Iron-water shielding tank refrigerator; 17 -- Steam generator compartment; 18 -- Circulation pump compartment; 19 -- Limonite concrete shielding; 20 -- Steam pipe compartment; 21 -- Control and protection rod servomotor compartment.

Figs 12 and 13 are diagrams of radiation shielding for nuclear reactors of different power.

As an example of biological shielding of ship reactors let us consider the NPP of the icebreaker "Lenin".

The arrangement of the NPP and its shielding were selected after reworking a large number of variants. The shielding consisted of a selection of stainless steel plates in water and partially concrete with a limonite ore filler ($Fe_2O_3 \cdot 3H_2O$) steel plates were selected as shielding for the primary heat transfer agnet loops. Experiments carried out on a reactor with an acitve zone analogous to the icebreaker reactors showed that to retard neutrons and gamma rays formed through neutron capture in iron, the optimal iron-water combination is one in which the ratio of volume concentrations $Fe:H_2O$ lies in the range from 50:50 to 65:35. In planning the shielding for the icebreaker reactor, exceptions were made in a number of cases in favor of a greater proportion of water. This leads to some deterioration of the shielding qualities with respect to neutrons, but reduces the weight of the shielding.

The iron-water combination is installed in a single tank filled with distillate which circulates over a closed loop, surrendering the heat accumulated in the shielding to a secondary heat transfer agent (auxiliary loop) in a special

heat exchanger. The entire loop with the distillate in the iron-water combination tank (inner cooling loop) is shielded with steel.

In connection with the fact that in the first loop the water (during reactor operation) has a great specific activity due to N^{16} nuclei which emit hard gamma rays, all of the primary-loop equipment and connecting pipelines are shielded with steel plates 380-420 mm in thickness. The arrangement of the equipment in the primary technological loop of the NPP, the basic iron-water and concrete and supplementary steel shielding are shown in Fig 14.

In calculating the radiation shielding for reactors, it was assumed at the start that the total neutron flow and gamma-ray stream from the active zones of the reactors were $2 \cdot 10^{13}$ neutrons/cm^2sec and $3 \cdot 10^{13}$ mev/cm^2sec, respectively.

The total thickness of shielding from active-zone radiation in the direction of the living compartments consists of 900 mm of steel and 980 mm of water.

8. Shielding Checks and the Construction of Isodosal Diagrams

In planning ships with NPP and sketching out the general location and arrangement of equipment, it is necessary to carry out check calculations of the radiation habitability of compartments [see note] outside the shielding contour. [Note: Let us agree to define the term "radiation habitability" as the characteristic of the radiation environment which can be used as a criterion for the possibility of the presence of the servicing personnel in a given area or ship compartment during a given period].

The absolute values of radiation streams with normal operation depend on reactor power, and if the NPP consists of several reactors, on the total power of the simultaneously functioning reactors. Hence we determine the maximum radiation flow from the basic sources -- the active zone and technological loop elements. In particular, for a water reactor with water under pressure (with the exception of the active zone) these are the heat exchangers, steam generators, pipes in the first loop, etc., having large outer surfaces (pipes with a diameter exceeding 100-150 mm), etc. Further, on the basis of the general design of the ship, a list is made of the compartments for which it is necessary to determine the radiation habitability. The attenuation of penetrating radiation beyond the shielding as a result of passage through metal partitions, decks, and large structures and pieces of equipment, mountings, diesels, turbines, generators, -- usually not taken into account in calculation will yield a certain reserve with respect to the shielding thickness. It is also necessary to take into consideration from the cisterns holding waste and radioactive deactivation water,

even if these have their own independent biological shielding.

The checks should be carried out for a number of parallel planes in various directions. Usually it is sufficient to carry out calculations of shielding in three planes along mutually-perpendicular directions: the deck plane, the bulkhead plane, and strake planes.

The results of calculations are tabulated in two tables samples of which are presented below. Table 13 indicates the results of calculations of radiation levels of radiation sources at various distances from the biological shielding surface. Table 14 contains the average value of radiation in the given compartment in terms of maximum permissible doses of occupational radiation over an 8-hour period, making it possible to determine the corresponding degree of radiation habitability.

Table 13

Sample Form for Recording Calculations of NPP Radiation Shielding

Плоскость (A)	Направление (B)	Основные излучающие поверхности источников проникающего излучения (C)	Мощность дозы проникающих излучений на расстоянии в метрах от наружной поверхности радиационной защиты, бэр/час (D)				
			0	1	2	3	10
Шпангоутная 110 шп. (E)	В корму (F)	Парогенератор Циркуляционные насосы № 1 и 2 Главный паропровод (G)	0,075	0,06	0,05	0,025	0,0025

A = Plane; B = Direction; C = Basic radiating surfaces of penetrating radiation sources; D = Dose of penetrating radiation at the distance in meters from the outer surface of shielding, reb/hour; E = Bulkhead 110; F = Toward stern; G = Steam generator; Circulation pumps Nos 1 and 2; Main steam pipeline.

According to the length of presence of service personnel in ship compartments, it is possible to class the latter in three categories:

1) constantly inhabited -- compartments in which the personnel live and rest (cabins, galley, sick bay, mess halls, lounges, etc.);

2) service areas -- compartments in which personnel remain during watches, but not more than 8 hours a day;

3) periodically visited areas -- compartments in which the personnel remain periodically, but not over 4 hours a day.

Table 14

Sample Form for Recording Calculations of NPP Radiation Shielding

Номер помещения и его координаты (A)	Наименование помещения (B)	Длительность посещения обслуживающим персоналом (C)	Средняя величина мощности дозы проникающих излучений в предельнодопустимых дневных дозах (D)
Правый борт, (E) 1 Верхняя палуба, 4 (F) Шпангоуты 120—128 (G)	(H) Пост энергетики	(I) Постоянно	0.3

A = Compartment number and coordinates; B = Compartment name; C = Presence of service personnel; D = Average radiation dose (maximum permissible daily amount); E = Starboard gunwale 1; F = Upper deck 4; G = Bulkheads 120-128; H = Power plant watch station; I = Constant.

It should be expected that calculations of this type will not be too precise; however, taking into account the available engineering "reserve", the results can be taken as satisfactory if carried out with an accuracy of ±25%.

Fig 15 shows some possible isodosal diagrams. The numbers on the isodosal curves conditionally indicate the radiation levels expressed in terms of maximum permissible 8-hour occupational radiation doses. It is particularly important to plan radiation shielding so that the radiation levels drop of maximally in the direction of living quarters. Some excess in the levels of penetrating radiation in the direction of the hold or side cisterns or other uninhabited compartments: storage compartments, tanks, ventilation ducts, etc., is permitted.

As is known, the flow of penetrating radiation rapidly decreases with distance from the surface of the shielding. At a distance of 20 m, radiation levels have decreased tens of times. Hence follows the inevitable conclusion of the desirability of maximum removal of the reactor cubicle from the ship's living and service quarters. Upon fulfillment of this condition, there is a considerable simplification of the problem of localizing the spread of radioactivity and the maximum reduction of the radiation levels even in periodically-frequented compartments.

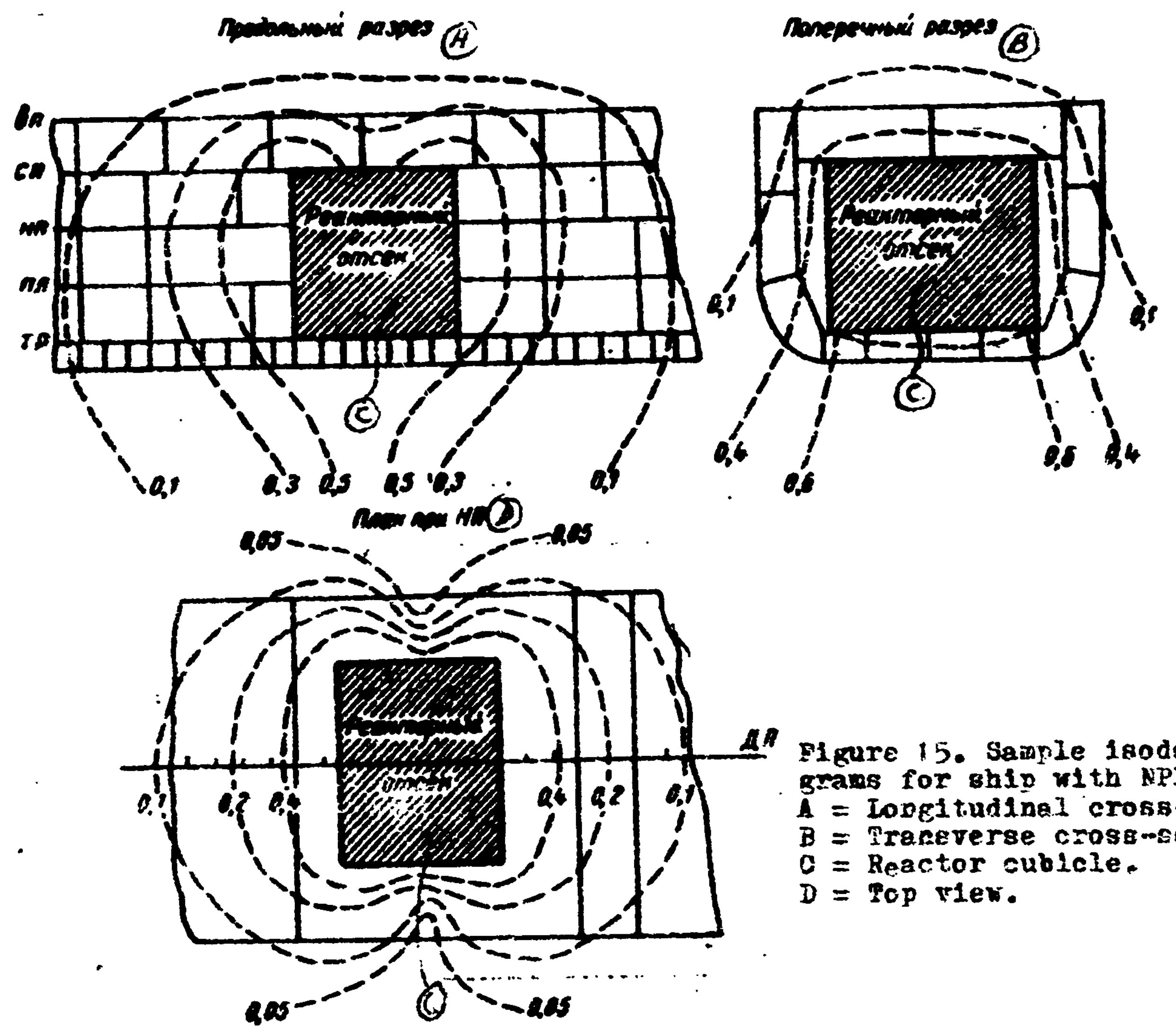

Figure 15. Sample isodosal diagrams for ship with NPP.
A = Longitudinal cross-section;
B = Transverse cross-section;
C = Reactor cubicle.
D = Top view.

Following practical measurement of isodosal charts, dosimetric equipment is used to determine the permissible length of presence of personnel in the NPP compartments. The time is calculated from the formula

$$t = D/P,$$

where D is the maximum permissible daily dose of occupational radiation, at present equal to 0.017 reb, and

P is the gamma-radiation dose, in r/hour.

For the sake of convenience, it is possible to make use of the curves shown in Figs 16 and 17, calculated for a gamma ray dose from 10^{-3} to 3 r/hour.

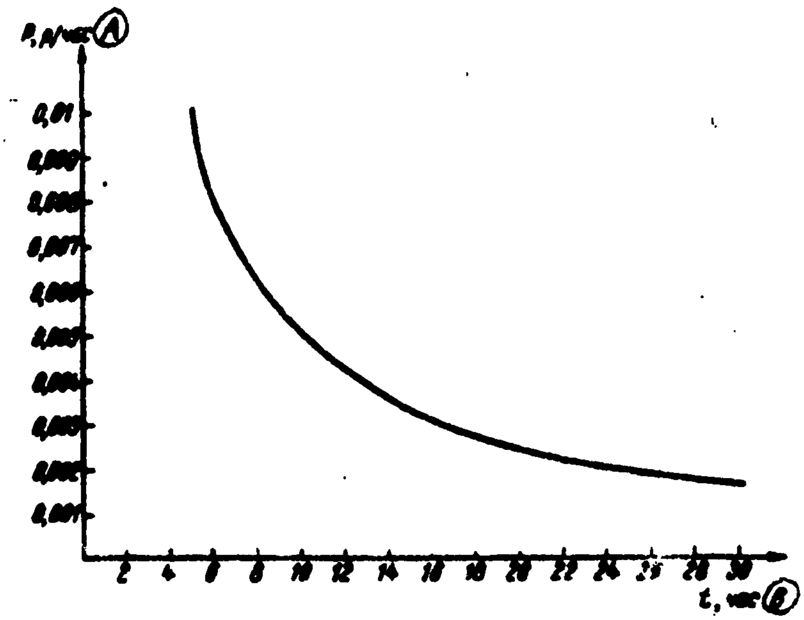

Figure 16. Curve of permissible time of presence t of service personnel with doses P of gamma radiation from 0.001 to 0.01 r/hour. A = P, r/hour; B = t, hours.

Under conditions of practical exploitation of a ship NPP, the permissible time of personnel presence in the reactor compartments must be controlled depending on the radiation environment in each actual area according to the data of quarterly measurements and emergency measurements under conditions which warrant this.

As examples to illustrate two different solutions of the shielding problem, it is possible to use the plans for the Swedish atomic tanker and the Soviet atomic icebreaker "Lenin".

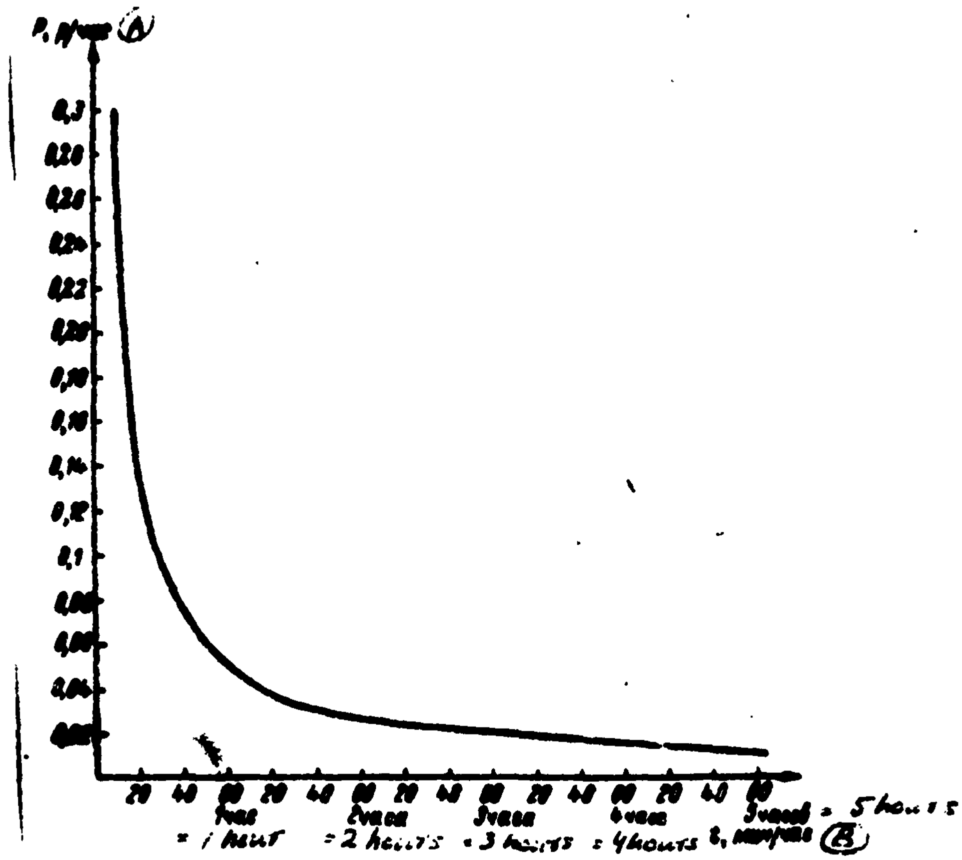

Figure 17. Curve of permissible time of presence $\underline{t}$ of service personnel with doses P of gamma radiation from 0.01 to 0.3 r/hour. A = P, r/hour; B = t, min/hour.

The great length of the tanker and the distribution of living and service compartments in the stern characterixtic of this type of vessel have made possible the favorable placement of the reactor cubicle at a distance of about 70 m from the nearest living compartment (Fig 18). A different configuration was used in the "Lenin" (Fig 19). The hull of the icebreaker is fairly short, and as distinct from the tanker, is full of machinery and equipment. As a result, it was not possible to place the reactor cubicle at the most desirable distance from the living and service quarters, which necessitated the use of more shielding.

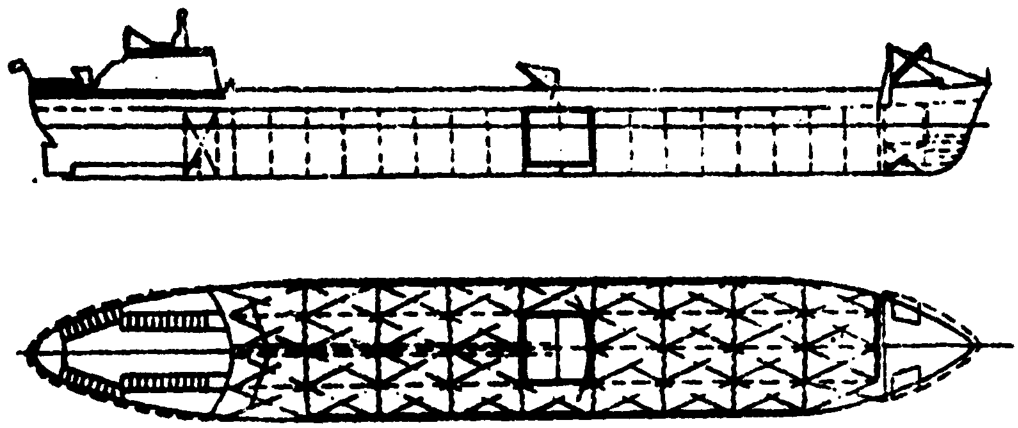

Figure 18. Location of reactor cubicle on the Swedish atomic tanker.

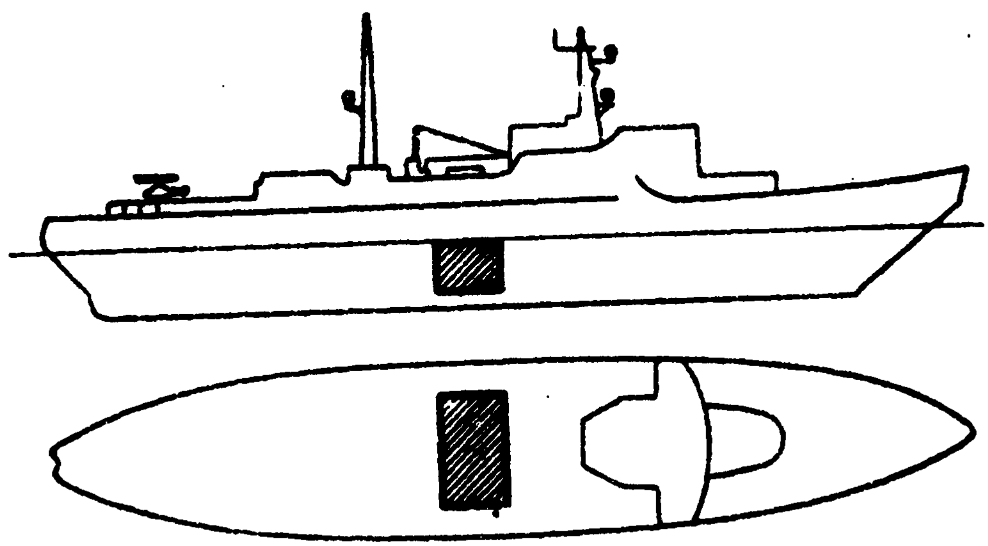

Figure 19. Location of reactor cubicle on the atomic icebreaker "Lenin".

Chapter IV

SOME INFORMATION ON DOSIMETRIC APPARATUS

9. General Remarks

The use of apparatus for controlling the radiation state of a ship with a NPP is a new field presently in the stage of development. However, ship dosimetry undoubtedly to a great extent depends on the experience accumulated in the instrument design industry in developing and constructing analogous devices for the atomic industry, mining, physics research, medicine, laboratory needs, etc. Usually these devices are called dosimeters, although strictly speaking this name is applicable only to those of them which measure ionizing radiation doses. In practice it is also necessary to measure streams of nuclear particles, the concentration of radioactive materials, etc., for which we employ counters, radiometers, roentgen meters (r-meters), and other devices.

According to purpose, dosimetric devices can be broken up into six basic groups:

1) dosimeters -- devices to measure doses of penetrating radiation (gamma radiation or neutron streams);

2) radiometers -- devices to measure activity, i.e., the amount of radioactive substances;

3) r-meters -- devices to measure the strength of gamma radiation doses;

4) devices to measure neutron streams;

5) devices to measure radioactive gas concentrations;

6) devices to measure concentrations of radioactive aerosols.

As a rule, any single-channel dosimetric device (device for measurement at a single point) can be reduced to the following block scheme: pickup, triggering detector of ionizing radiation, recording and signalling device, and power supply (Fig 20).

All dosimetric apparatus is based on the principles of electronics and radio, and is rather complicated on the whole. It makes wide use of electronic high-gain amplifiers, highly-sensitive electronic relays, counters, etc.

A large number of device components in combination with these qualities leads to the insufficient stability of their parameters and relatively low reliability, especially if we take into account specific shipboard operating conditions. There are frequent minor variations in parameters of the device components -- capacitors, resistors, electronic tubes, detectors, -- which does not lead to a direct disruption of device operation, but distorts the readings. Two similar serially-constructed devices can have a significant divergence of output parameters. The precision of modern dosimetric equipment does not exceed 10%. Hence it follows that the graduation of dosimetric devices must by systematically checked with recording of the resulting data in the calibration log.

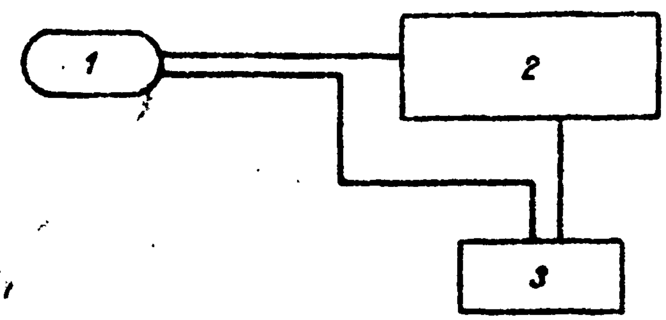

Figure 20. Block diagram of single-channel dosimeter.
1 -- Pickup; 2 -- Recording and signalling device; 3 -- power supply.

Dosimeters should be graduated in such a way as to include the necessary radiation spectrum and intensity ranges. Graduation is performed either by comparison with a standard dosimeter or with the aid of a radioactive standard sample.

To control the functional ability of the apparatus as well as to roughly check the graduation, use is made of special low-activity radioactive preparations usually supplied together with dosimetric equipment. In particular, to check gamma dosimeters, cobalt-60 is used as the gamma source; neutron dosimeters are checked by means of radioactive beryllium or polonium-beryllium samples.

10. Ionizing Radiation Detectors

Pickups. The purpose of pickups is to produce some electrical quantity or its variation: e.g., the variation of voltage or current, a pulse, a variation of resistance, etc., dependent on the intensity of ionizing radiation in the given area. For this purpose pickups employ special detectors of ionizing radiation: ionization chambers, gas-discharge, and scintillation counters. Below we consider the operating principles of these devices.

Ionization chambers. Dosimetric devices use the phenomenon of variation of gas conductivity depending on the intensity of ionizing radiation acting on the gas.

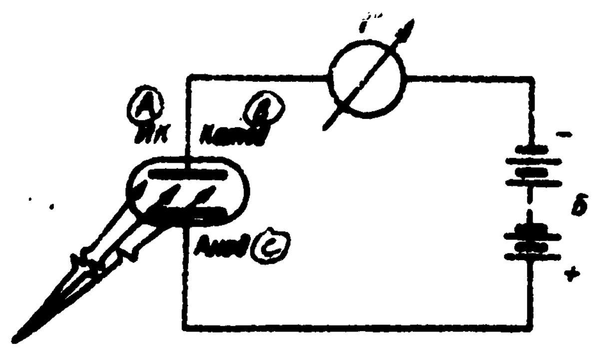

Figure 21. Diagram of ionization current measuring scheme. A = Ionization chamber; B = Cathode; C = Anode; Γ -- Galvanometer; Б -- Battery.

Figure 21 shows the simplest circuit which makes possible the measurement of the electrical conductivity of a gas. The ionization chamber (ИК) is usually a closed volume containing two electrodes and filled with a gas or mixture of gases up to a certain pressure. Under the action of charged particles passing through the ionization chamber, (as well as gamma rays or neutrons), the electrically- neutral gas atoms are ionized, forming positively- and negatively-charged particles (ions). Under the action of the applied electric field, the ions travel toward the anode and cathode, producing the electrical current registered by the galvanometer Γ. The dependence of this ionization current on the potential difference applied to the chamber is shown in Fig 22. On portion I of the curve, the current I, i.e., the number of ions reaching the electrodes, is proportional to the applied potential difference U in accordance with Ohm's law. On section II, the current $I = I_H$ is independent of U.

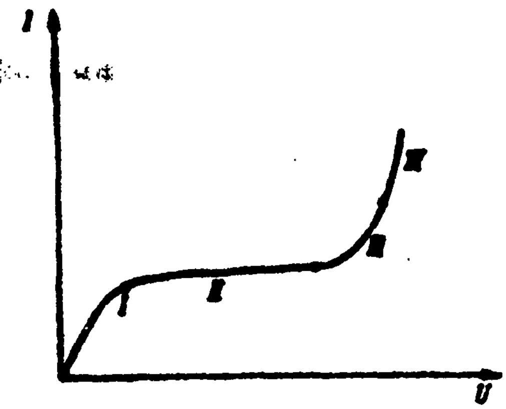

Figure 22. Curve showing dependence of ionization current I on the potential difference applied to the ionization chamber.

I_H is called the saturation current and corresponds to a state of the ionization chamber where all of the ions formed in it reach the electrodes. The absolute value of the saturation current depends solely on the intensity of the ionizing radiation. On portion III of the curve, the ionization current once again increases sharply due to the so-called secondary or shock ionization produced in the gas by the ions themselves due to their acceleration to a sufficiently high energy. Further increasing the applied voltage, we enter portion IV of the curve, corresponding to the phenomenon of electrical breakdown analogous to a short circuit inside the chamber. Usually ionization chambers operate in the voltage range corresponding to the plateau portion of the curve (II) when the ionization current is proportional to the strength of the dose of ionizing radiation under investigation.

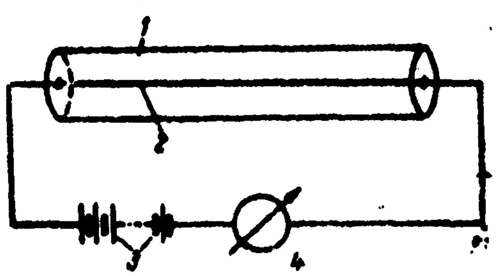

Figure 23. Diagram of gas-discharge counter. 1 -- cathode (metallized inner surface of glass tube or thin-walled metal tube) 2 -- anode; 3 -- battery; 4 -- measuring device.

Gas-discharge counters. At present, wide use is being made of Geiger-Muller gas-discharge counters. Gas-discharge counters are ionization chambers which operate under conditions of section III of the curve in Fig 22, i.e., under conditions of gas amplification. The ratio of the size of the current pulse to the initial ionization is called the gas amplification factor. The mechanism involved in the operation of the gas-discharge counter is the following. The ionizing radiation passing through the sealed tube produces a certain number of ion paris which begin to move toward the appropriate electrodes under the influence of the electric field (Fig 23). As a result of the high electric field intensity in the tube, the energy acquired by the ions as they are accelerated in the space between the electrodes becomes sufficient to produce secondary ionization. The current flowing through the counter increases sharply upon the collision of such accelerated ions with neutral particles of the filler gas, and the current pulse thus produced can be registered by means of a special circuit. The length of the pulse in a gas-discharge counter is very small (about 10^{-4}-10^{-5} sec), which makes it possible to register both single ionizing particles and a large number of particles per unit time.

Usually, gas-discharge counters are cylindrical in shape. The outer metallic shell is the cathode, while the filament running along the axis of the cylinder is the anode. The necessary potential difference is applied across the filament and shell. The counter pulse can be amplified with the aid of an ordinary electronic tube.

A diagram of a gas-discharge circuit with amplifier is shown in Fig 24.

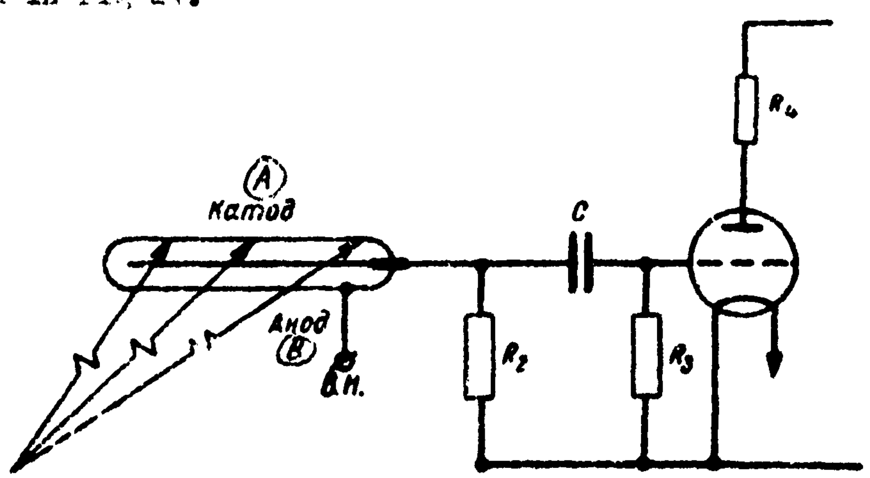

Figure 24. Diagram of gas-discharge counter. A = Cathode; B = Anode.

Scintillation counters. The operation of scintillation counters is based on the use of the phenomenon of the excitation of the atoms of certain substances and the emission of light quanta upon passage through them of ionizing radiation. The return of the atom from the excited to the normal state is accompanied by a scintillation which can be registered by means of a photomultiplier.

A number of organic and inorganic substances exhibit scintillation properties; it is quite significant to note that the phenomenon takes place in both solid and liquid and gaseous materials. Scintillation counters are used in particular to measure gamma and neutron radiation. The scintillators most widely used for this purpose are sodium iodide crystals activated with thallium -- NaI(Tl) and zinc sulfide crystals activated with silver -- ZnS(Ag). In particular, fast neutron streams are measured by means of polystyrol tablets infused with zinc sulfide crystals. A block diagram of a scintillation counter is shown in Fig 25. In scintillator 2 irradiated with ionizing radiation there arise light flashes whose photons strike the photocathode of multiplier 3. As a result of the photoeffect [see note], the latter emits electrons, which are accelerated by the electric field, strike the first dinode $Д_1$ and dislodge additional electrons from it. These are in turn accelerated, strike the second dinode, etc., all the way to the final dinode Д . The greatly-amplified pulse (the photomultiplier gain may reach 10^6-10^8) formed across the load resistor of the photomultiplier is sent on to a special registering device. [Note: Broadly speaking, the photoeffect refers to the appearance or variation of an electric current in a circuit upon the issumination of one of its elements. The physical nature of this phenomenon consists in the fact that the light incident on the surface of the element dislodges electrons which are called photons. More detailed information may be found in any physics text or a book on the theory of electrical phenomena in gases and in a vacuum.]

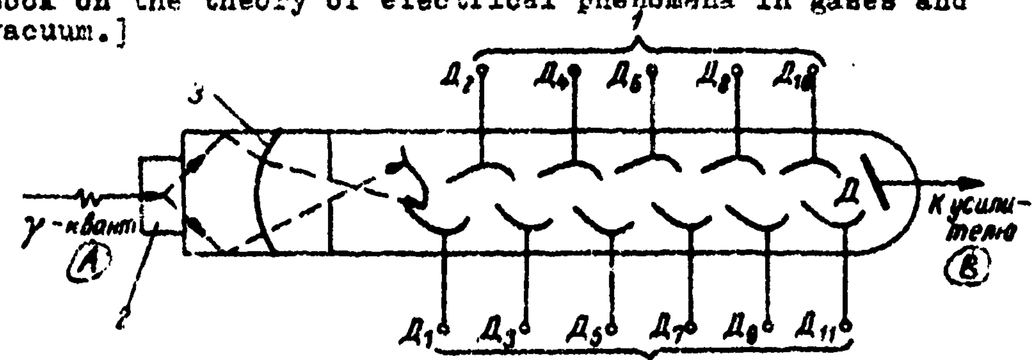

Figure 25. Block diagram of scintillation counter. 1 -- intermediate anodes (dinodes); 2 -- scintillator; 3 -- photocathode; A = Gamma quantum; B = To amplifier.

11. Control-Registering and Measuring Devices of Dosimetric Apparatus

Stationary dosimetric instruments are either single- or multi-channel, depending on their purpose. A single-channel device makes it possible to measure ionizing radiation at a single point, while multi-channel devices provide a means of successive measurement in a number of places. In addition to a detector, dosimetric instruments usually include signalling, registering, and measuring devices which represent standard electronic amplification circuits. Fig 26 shows a block diagram of a ten-channel dosimetric device. Ten pickups are hooked up to an amplification-registering device (УРУ) which amplifies the pulses, sending them on to the signalling device. The signalling device (СУ) assures the actuation of the appropriate channel of the threshold light or sound signalling system. The measuring device (ИУ) has at its output a properly graduated measuring instrument -- a direct-reading micro-ammeter switched automatically or manually to the required channel. Measurement with the aid of a pointer device can be replaced by measurement of signal amplitude on the screen of an electronic oscilloscope whose use allows observation and measurement along several tens of channels simultaneously. Modern dosimetric multi-channel systems make possible simultaneous control of several types of radiation along hundreds of channels.

12. Measurements of Radioactive Gas and Aerosol Concentrations

Internal irradiation of the human organism due to active materials ingested in respiration, eating and drinking, and through the skin, is many times more harmful than external irradiation with the same quantities of radioactive materials. Of the three aformentioned means of entry of radioactive matter into the organism, the first is the most dangerous. For this reason, the maximum permissible concentrations (MPC) of radioactive gases and aerosols in the air of service compartments are extremely small quantities. According to modern international rules they are 10^{-11} curie/liter for gases and 10^{-13} curie/liter for aerosols.

The origin of radioactive gases was considered above, in the chapters describing physical processes taking place in reactors.

Aerosols are solid particles in suspension in the air. The sizes of aerosol particles are extremely minute -- their diameters range from 0.1 to 0.001 microns. As a result, they can remain in the air for a long time, subject to the law of Brownian motion. Radioactive gases spread in the air by

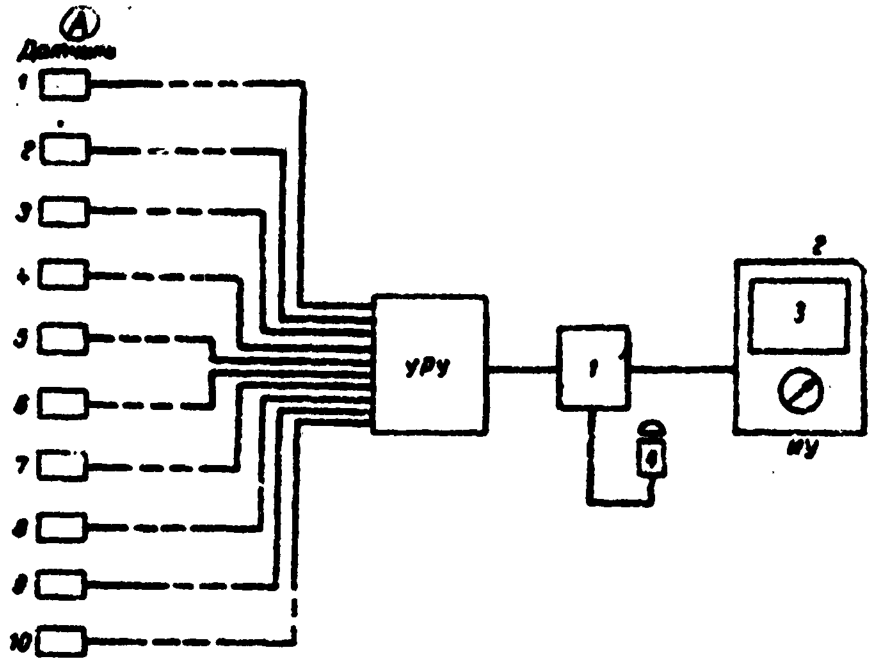

Figure 26. Block diagram of ten-channel dosimetric device. 1 -- Signal block; 2 -- Measuring block; 3 -- Oscilloscope screen; 4 -- Bell; УРУ -- Amplifying registering device. A = Pickups.

by ordinary diffusion. If we take into account that the average value of natural radioactivity in the air is on the order of 10^{-13}-10^{-14} curie/liter, it becomes clear that dosimetric devices which assure control over gas and aerosol concentrations in air must be extremely sensitive. The methods of measuring gas and aerosol activity is specific and differs from the methods of measuring penetrating radiation.

A skeleton diagram of a gas radioactivity meter is shown in Fig 27. The instrument pickup -- a gas-discharge counter -- is placed in a special "counting" enclosure through which the controlled air is pumped. The dimensions and shape of the counting enclosure determine to total activity of the air in it at a given instant, and therefore the radiometer sensitivity. It is not hard to show that within certain limits the instrument sensitivity will be proportional to the volume. The device is graduated only in accordance with a specific counting enclosure, for which a special calculation is carried out.

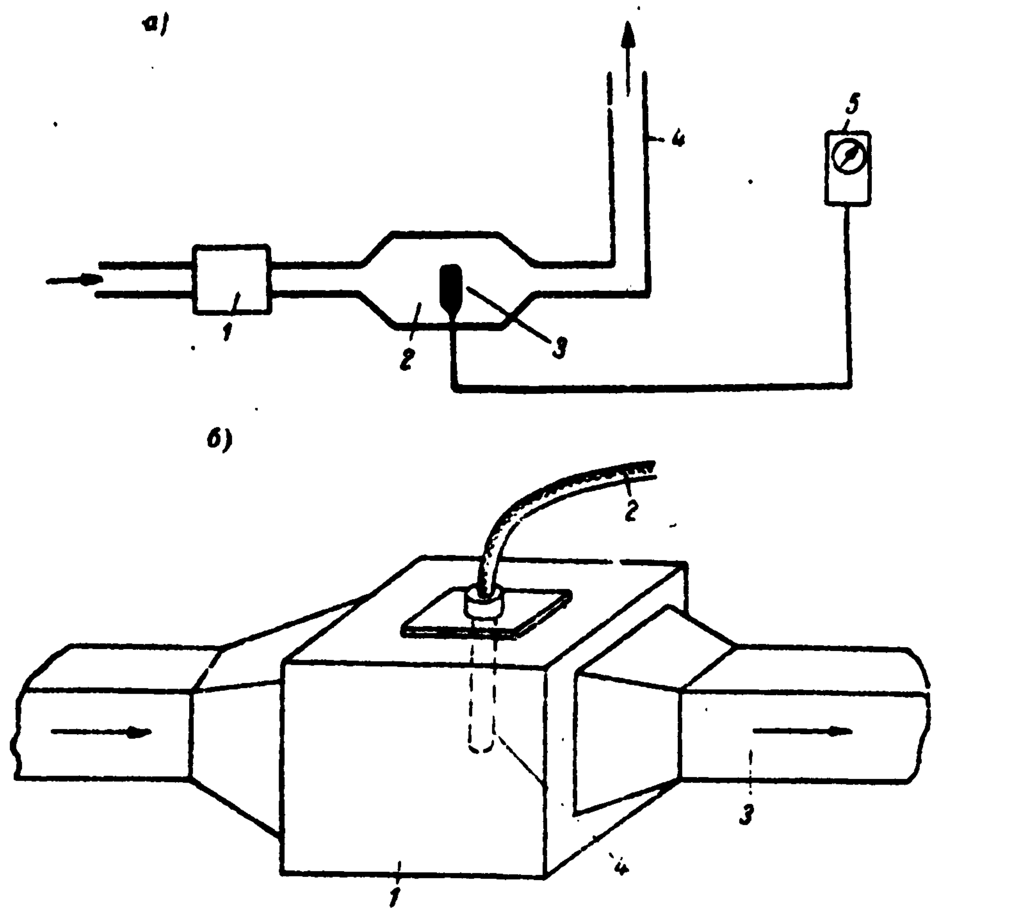

Figure 27. Skeleton diagram of gas radioactivity meter.
a -- Skeleton scheme of aerosol meter: 1 -- Antiaerosol filter; 2 -- Counting enclosure; 3 -- Radiometer pickup; 4 -- Ventilation channel; 5 -- Radiometer measuring device; b -- Structure of pickup component in counting enclosure: 1 -- Counting enclosure; 2 -- Cable; 3-- Ventilation channel; 4 -- Radiometer pickup.

To avoid the buildup of the radioactive gas detector background as a result of the accumulation of aerosols in the air ducts ahead of the counting volume, anitaerosol filters are installed in the latter. The counting enclosures are usually made of stainless steel with a polished inner surface. This cuts down on the settling of aerosols still passing through the filter and simplifies the periodic deactivation necessary for the elimination of background. The external effect of the gamma background can be reduced with the aid of the background compensation circuit employed in such instruments.

The operation of most aerosol devices is based on the periodic measurement of the total activity of aerosols settling over a given time period on a special filter mounted in the controlled air duct. The principle of radioactive accumulation makes it possible to increase instrument sensitivity and to control even very small aerosol concentrations. Aerosols can settle due to purely mechanical filtration or through the use of electrostatic filters. The effectiveness of filter operation depends on the sizes of aerosols and the rate of air motion. In a number of modern filters for gathering radioactive aerosols, the efficiency exceeds 99%. In conclusion we shall describe a system of aerosol monitoring most applicable in modern ship NPP practice. A diagram of such a system is shown in Fig 28.

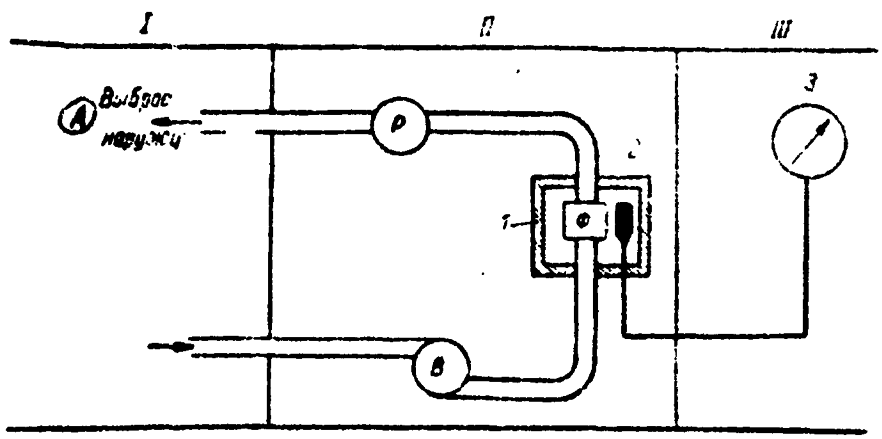

Figure 28. Diagram of system for measuring radioactive aerosol concentration. I -- Controlled compartment; II -- Ventilator section; III -- Central dosimetry station; 1 -- Shielding screen; 2 -- Radiometer pickup; 3 -- Radiometer measuring instrument; B -- ventilator; Ф -- Interchangeable filter; P -- Flow gauge. A = Blowout.

The controlled air is pumped by a special ventilator B through filter Ф near which the radiometer pickup is mounted. In order to avoid the spread of activity, the air ducts, ventilator, filter, and radiometer pickup, as well as the air flow meter P are hermetically sealed and placed where possible, with the exception of the instrument pickup, outside the uncontaminated parts of the ship, best of all -- in the contaminated ventilator compartments. The air taken for control is usually blown outside or into the same space

from which it was drawn. Knowing the amount of air passing through the filter from the readings of flow meter P, and having measured the total activity over a definite span of time, it is possible to determine specific aerosol activity.

The filter is usually in the form of a ribbon wound by a small remote-control motor switched on at the dosimetry station. This makes possible the periodic replacement of filter elements and the repetition of remote measurements without entering the controlled compartment.

We could describe a number of other dosimetric devices and methods of measuring aerosol concentration, but this is beyond the scope of our work; descriptions will be found in the journals and in special publications.

13. Portable Dosimeters

In their functional principles, portable dosimeters do not differ from stationary instruments. The block diagram of a portable device likewise includes a pickup consisting of a radiation detector and a registering-measuring component connected to it by means of a flexible cable. Portable dosimeters are powered as a rule by dry cells or storage batteries. The only difference is in portable devices for measuring radioactive gas and aerosol concentrations in the air and the activity of water.

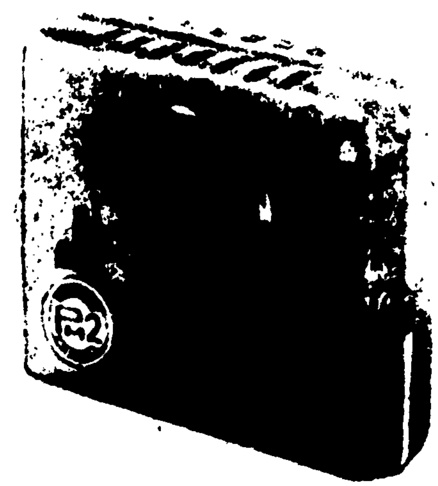

Figure 29. RM-2 pocket ionizing radiation indicator.

Inasmuch as the measurements carried out in these cases are with reference to a volume which determines the instrument sensitivity, only the counting enclosure can be portable. It is constructed of materials which can be easily deactivated (e.g., plastics or glass), taken to the controlled areas and there filled with the air or water under study. Then it is sealed and taken to the laboratory.

There it is measured with the aid of a radiometric installation. The latter consists of a radiation detector sealed in lead or steel shielding to lower the external gamma background which adds a measurement error, and the appropriate electronic apparatus. When it is necessary to measure very small aerosol concentrations, portable dosimeters are also used in conjunction with the above method of activity accumulation on a filter. In this case, the portable instrument is equipped with a small air blower and antiaerosol filter. Filter changing, actuation, and shutoff of the air blower are performed manually.

14. Individual-Use Dosimeters

For systematic determination of total absorbed radiation doses, as well as individual control of the radiation environment in the work area, the personnel servicing the reactor are provided with various miniature dosimetric devices. The following are the basic ones mong these.

Condenser chambers. Before use, the devices are charged to a certain definite potential. In a field of ionizing radiation, the condenser discharges as the result of ions formed within it. From the remaining condenser charge measured with a special instrument, the radiation dose is determined. In appearance, this device resembles a fountain pen.

"Nutcracker"-type gamma-beta indicator. This is a halogen counter in combination with a thyratron and an ordinary earphone. Radiation is registered visually by observing thyratron flashes and aurally according to the number of clicks in the phone, which is proportional to the intensity of radiation. The device is usually supplied with a conversion table which makes it possible to convert the number of clicks per unit time into the size of the dose (r/hour). The device is powered by a dry cell. It must be noted that such an indicator provides only a qualitative estimate of ionizing radiation. Fig 29 shows a device of this type.

Electroscope device. The total radiation dose is determined visually according to the change in the position of electroscope leaves relative to each other; the electroscope is charged in advance and placed in a glass tube with an optical system. In appearance, the device looks like a mechanical pencil.

Film badges. The total radiation dose is determined from the degree of blackening of a photosensitive piece of film placed in a special light-sealed holder due to the action of ionizing radiation.

Chapter V

THE POSSIBILITY FOR THE SPREAD OF RADIATION OVER A SHIP WITH AN NPP AND METHODS OF COMBATTING IT

15. General Remarks

The radiation environment on a ship with an NPP both under conditions of normal exploitation [see note] and in an emergency, depends primarily on the type of reactors chosen. Indeed, both forms of radiation danger -- ionizing radiation and radioactive contamination are the result of physical processes in the active zone of reactors which also lead to the activation of the heat transfer agent, i.e., the spread of radioactivity beyond the active zone shielding. The basic causes of heat transfer agent activation are, as is known, the process of neutron absorption by the agent, the activation of the erosion and corrosion of metal parts in the primary technological loop, and in emergency conditions -- the emergence of highly-radioactive fission fragments through crevices in the heating elements. For example, reactors with water as the heat transfer agent produce induced activity -- relatively rigid gamma radiation (with an energy of about 7 mev) due to active nitrogen according to the O^{16} (n,p)N^{16} with a half-life of 7.35 sec. Reactors with a metallic heat transfer agent, e.g. sodium, produce the basic induced radioactivity due to active sodium according to the reaction $Na^{23}(n,\gamma)Na^{24}$. This isotope is characterized by weaker gamma rays, but with a long half-life, equal to 14.8 hours. Finally, reactors with an organic heat transfer agent are characterized by a low induced gamma activity. Hence we see that with equal reactor power, the thickness of shielding will differ in every case. Radioactive contaminations and their qunatity in the event of a breaking of the hermetic seal of the primary loop, and therefor prevention and control methods, also differ. [Note: Normal NPP exploitation is maintained provided the primary technological loop and the shells of the heating elements are hermetically sealed].

In addition, the radioactive environment aboard ship depends on the design solution of the entire complex of NPP

equipment and the auxiliary apparatus, including its placement aboard the vessel. Actually, in the case of a water-water reactor, in the case of a major emenrgency we can have a contamination of the steam in the secondary loop, which creates a radiation danger in the usual service compartments.

For a reactor with an organic heat transfer agent, such a danger is much less acute, which makes possible a simpler solution to the general problems of NPP placement in ship compartments.

We can assume that emergencies in the case of reactors with metallic heat transfer agents will be significantly more dangerous from the standpoint of radioactivity. This, in particular, was confirmed by tests of the US nuclear submarines.

Thus, in the solution of problems of assuring radiation safety aboard ships with nuclear plants, the approximate spectral composition of radioactive isotopes in the primary loop is determined in advance on the basis of the type of reactor selected. This determination must be made with due regard to both normal exploitation and emergency regimes. Further, on the basis of the actual design of the ship, a determination is made of the possible ways of propagation of penetrating radiation and radioactive substances into the living and service compartments. Then, measures are incorporated to prevent this spread; this may involve a radical alteration of the plan of the ship and its equipment and systems.

At the present time, no firm choice has yet been made as to the types of reactors which best satisfy the conditions imposed on ship reactors -- economy of operation, minimal size and weight, simplicity of design, and ability to operate satisfactorily in rough water and at various tilt angles with absolute reliability and safety.

On the basis of published domestic and foreign materials, it is nevertheless possible to conclude that nuclear ship design will continue to be based for some time to come on heterogenous slow-neutron reactors with heating elements of natural and slightly enriched uranium, cooled by water under pressure.

It is known that work is being done on so-called "boiling reactors", i.e., reactors in which the steam going into the turbine is formed directly in the active zone, reactors with an organic heat transfer agent, as well as gas-cooled reactors. The use of boiling-water reactors will be possible in practice only after the development of a fully-automated turbine, inasmuch as it is fed with active steam, and must therefore be located within the rigid-regime zone [Note: For a definition of the so-called rigid-regime zone on nuclear ships see p 127], as well as after the development of a reliable separation system which would prevent the entry of nuclear fission fragments into the turbine along with the steam.

It should be said further that in studying the possibility of the spread of radioactivity over an NPP ship, it is necessary to take into account the radiation danger which arises as a result of the appearance of liquid wastes in the process of deactivation of compartments, equipment, special clothing and shoes, and the bathing of personnel servicing and operating the NPP. Liquid radioactive wastes are present not only under conditions of emergency NPP operation, but also in the course of normal exploitation, which makes necessary the collection and drainage of even a small leak, as well as washdown deactivation. The difference consists solely in the fact that under normal NPP operating conditions, the washdown water is less in volume and of insignificant radioactivity.

Deactivation water can result in a radiation; this must be taken into consideration in planning.

16. Actual Sources of Penetrating Radiation and Radioactive Substances and Their Ways of Spreading Over the Ship

To assure radiation safety to the personnel of a nuclear vessel, the following basic requirements must be met:

1. The level of irradiation in constantly-inhabited compartments must be close to the normal background (due to cosmic rays and normal radioactive elements).

2. Under any conditions, the entry of radioactivity into the air of living and service compartments, as well as their contamination with radioactive substances over permissible levels must be excluded. For this purpose, in planning an NPP vessel, all spaces exposed to radiation danger must be grouped in a single isolated block. Access to the block is to be provided only by a special lock equipped with deactivation and monitoring equipment.

3. The basic and emergency NPP controls must be automated to the fullest possible extent in order to obviate the necessity of prolonged presence of personnel in the reactor cubicles in the event of NPP malfunction.

Let us consider in greater detail the question of the primary sources of ionizing radiation and the spread of radioactive materials over a vessel with a heterogeneous reactor with water under pressure (see Fig 10). The heat transfer agent in this plant is bidistilled water under a constant pressure of about 200 atmospheres. All of the primary elements -- reactor P, primary heat transfer agent pump ЦН, heat exchanger TO, and other structures, are enclosed in the closed radiation (biological) shielding contour БЗ. The secondary technological loop provides steam to the power

installations aboard ship, and under normal NPP conditions is non-radioactive. The third loop (not shown in Fig 10) provides heat for drinking and washing water, air-conditioning, etc. The presence of the primary and secondary loops is intended to prevent the spread of radioactivity and ionizing radiation beyond the shielding and the reactor cubicle as a whole under all conditions of NPP operation.

The primary sources of penetrating radiation are, as already mentioned, the elements of the primary NPP loop, including: reactors, steam generators, circulation pumps, primary-loop pipes and all related structures.

The primary sources of gas and aerosol contamination are all of the structural crevices in the complex of the primary technological loop.

Let us consider in detail the problem of radiation safety under conditions of normal NPP exploitation, as well as under emergency conditions.

The Radiation Environment Under Conditions of Normal NPP Operation and Exploitation

By normal NPP operation we mean operation under conditions of full hermetic seal of the primary technological loop. The most important and significant link from the standpoint of radiation safety are the heating elements, or, more precisely, their metallic shells which are usually made of aluminum, stainless steel, or zirconium. With heating elements in good condition, the activity of the heat transfer agent which in general determines the radioactive state of the NPP (not including the reactor considered separately) depends on two basic factors: the induced nitrogen activity with its low half-life which is dangerous only when the reactor is operating, and the active products of metal corrosion in the primary loop.

Hence it follows that the raciation danger is determined by the total gamma radiation due to induced activity and the activity of corrosion products. The basic portion of the total gamma activity is made up of the induced activity, equal to about 0.2 curies/liter according to the data of the icebreaker "Lenin". The specific activity of corrosion products in the equilibrium state reaches 10^{-4} curies/liter, i.e., a total of about 0.1%. It must be remembered, however, that the half-life of the corrosion products is significantly higher than that of the isotopes of induced water radioactivity. As a result, the cold-reactor heat transfer agent retains this activity. These half-lives are: 27.8 days for chromium, 46 days for iron, etc. (as the components of stainless steel).

It must be added that even under normal conditions the heat transfer agent is found to contain radioactive gases: xenon, krypton, and iodine. This can be explained by the

decay of nuclear fuel traces on the heating-element surfaces which are unavoidable with modern means of producing the latter and the presence of the so-called gas permeability of the heating element shells -- microcrevices which cannot be visually detected. With a hermetically-sealed primary loop, this insignificant gas activity, as well as the activity of corrosion products, creates no radiation danger directly. Also non-dangerous are the alpha particles from the nuclear fuel, inasmuch as they are practically localized within the active zone.

With a normal reactor regime, it is possible to assure radiation safety also with respect to neutron emission with its high penetrating power. The active reactor zone is surrounded with special radiation shielding and neutron reflectors which actually prevent the emergence of the neutron stram beyond the reactor above permissible levels. With the aid of adequate continuity of shielding, conditions are created which permit only an insignificant portion of the neutron stream to leave its confines; this residual portion is easily controlled with the aid of stationary neutron dosimeters and does not make for any radiation danger in the continuously-serviced ship compartments. An accidental emergence of neutrons can take place only in the direction of weak points in the neutron shielding, which on ships are oriented toward the non-serviced compartments, e.g., the sub-reactor compartments, cisterns, etc.

The radiation danger from gamma radiation is liquidated by enclosing the reactor with the entire primary-loop complex in a closed radiation (biological) shielding system calculated to prevent the gamma radiation level from exceeding maximum-permissible values beyond its confines. In the event sewage tanks for storing radioactive wastes of differing origin are located beyond the shielding system, they must be provided with reliable shielding of their own, calculated for maximum-possible total gamma activity of the wastes assuming that the tank is filled all the way to the top.

After the NPP reactors are brought up to full power, a check is made of shielding effectiveness with respect to penetrating radiation, and time limits are introduced for the presence of personnel in dangerous zones.

It is necessary to consider separately the problem of gas and aerosol beta activity. The fact is that with normal primary-loop operation, there is nevertheless some leakage of normal bidistillate from the unavoidable crevices in the primary-loop joints, which lead to the formation of beta-active aerosols in the air of the reactor cubicle. The available experience and calculations (including that from the "Lenin") indicate that even if leakage is at the improbable rate of several tens of liters per hour, the activity of the air in the cubicle equipped with the appropriate ventilation will not exceed 10^{-12} curies/liter. This corres-

ponds to about 3-5 times the maximum permissible concentration (MPC) of active corrosion products constituting the basic heat transfer agent activity under normal conditions (for stainless steel from which the primary-loop components are usually made, are chromium, manganese, iron, nickel, and other isotopes).

Actually, the true heat transfer agent leakage is on the order of fractions of a liter per hour, since the lack of a proper seal is mainly the result of local thermal weakening of joints in the primary loop upon radical changes in reactor operation regimes. This leakage can be controlled with the aid of dosimetric devices. In the presence of a broken seal in the radiation shielding, this small quantity of aerosol activity can nevertheless emerge into the neighboring inhabited compartments of the ship. But even low gas and aerosol activity as a result of the accumulation can be of some danger. Hence it is necessary to maintain careful dosimetric surveillance and localization of this activity in the limits of the reactor cubicle, and moreover, within the limits of individual compartments. The methods of localizing gas and aerosol activity will be treated below.

Summarizing the present treatment of the radiation environment aboard a nuclear vessel with normal NPP operation, we can draw the following important conclusions:

1) penetrating radiation -- gamma rays and neutrons -- are not excessively dangerous beyond the limits of the shielding if it is well-designed. Service personnel can remain in a number of reactor compartments for limited periods established by the radiation monitoring service;

2) gaseous radioactive materials formed with small leakages from the reactor compartment despite adequate shielding do not result in a radiation danger beyondthe compartment; the latter can be enetered for limited periods. The necessity of employing special pneumatic suits is likewise specified by the dosimetry service.

The Radiation Environment With Emergency NPP Operation

Matters are considerably more complex when it comes to NPP operation under emergency conditions, i.e., when large quantities of fission fragments entering with the heat transfer agent from the primary loop into the steam of the secondary loop or the air of the reactor cubicle contaminate the latter. The possible reasons for the emergence of radioactivity beyond the limits of the primary loop are as follows:

a) imperfect gas seals (microcrevices) in the heating element shells;

b) major damage (burnout, rupture) of the heating element shells;

c) breakage of hermetic seal of steam generators (heat exchangers between first and second loops);

d) breakage of hermetic seal at joints of primary loop or the piping, fixtures, etc.

Gas leakage was discussed above.

Before considering the remaining cases of disruption of primary-loop hermetic seals, it would be advisable to briefly indicate their common cause -- the phenomenon of intensified corrosion of inner metal surfaces of primary-loop structures. The fact is that water breaks up into hydrogen and oxygen ions under the action of radiation in the reactor. There takes place a chemical reaction involving their combination with the radioactive nitrogen resulting from the nuclear reaction $O^{16}(n,p)N^{16}$, to form nitric acid. As a result, conditions conducive to increased corrosion are created.

The rate of corrosion in the primary loop has not as yet been calculated precisely. It depends on many factors including the chemical activity of the heat transfer agent, and temperature and pressure in the primary loop,, as well as the quality of metal of primary-loop structures and the treatment of inner surfaces, physical characteristics of the active reactor zone, etc. In time, the specific activity of the corrosion products in the heat transfer agent rises to a definite limit corresponding to the attainment of an equilibrium state between the newly-appearing activity and the radioactive components which decay rather rapidly.

To lower the level of active contamination of the primary heat transfer agent, ion-exchange filters are used; these are special devices filled with sorbents (materials capable of retarding any ions, including radioactive isotope ions). Such substances are in particular certain organic resins. The operation of an ion-exchange filter is based on the fact that the atoms of radioactive isotopes in the primary loop always carry an electrical charge.

These ions chemically remove from the resins those ions which are most weakly bound, replacing them in the resin structure. Ion-exchange filters are usually used for the continuous purification of the heat transfer agent to remove the corrosion products from the primary loop. They can likewise be employed in any ship system for the purification of technical water and for deactivation and waste waters.

Ion-exchange filters are usually installed in the bypass to the primary-loop pipes. This makes possible the limitation of the accumulation of corrosive products and the substantial lowering of their specific activity in the heat transfer agent, thereby improving the radiation environment in general.

Damage to the heating element shells leads to direct contact of the heat transfer agent with the uranium. Uranium is itself chemically active, and is oxidized by hot water, becoming a powder. Expanding hygroscopically, the powder increases the size of the fissure and enters the heat transfer agent directly. The concentration of radioactive fragments in the latter in this case can reach very high levels -- tens of curies per liter. This renders further reactor operation impossible, since the radioactivity spreads quite rapidly over the entire volume of the primary loop. Hence we see how important the proper design of heating elements shells can be. If the remaining shells remain hermetically sealed, the emergence of fragment activity into the heat transfer agent will lead only to an increase in the radiation level in the primary loop. This can be allowed for in advance in the calculation of shielding or compensated by an increase in the thickness of biological shielding in this phase. However, the case of small primary-loop leakage can lead to a basically dangerous emergence of radioactivity in the air of reactor compartments. Precisely for this reason, it is necessary to have continuous control of heat transfer agent activity in the primary loop so as to make possible the immediate shutdown of the malfunctioning reactor.

The breakage of the steam generator seal which leads to the emergence of radioactivity from the primary loop into the secondary-loop steam is the most dangerous of all possibilities if it involves the emergence into the heat transfer agent of fragment activity from the damaged heating elements. Then the faulty steam generator and plumbing must be shut off immediately; the probability of such accidents is not high however.

There are several means of maintaining sound steam generator operation. It is possible to control the seal of each steam generator by means of a beta-dosimeter according to the activity of steam in the secondary loop. With proper generator operation, gas activity will not be registered in the steam. In case of eruption of the heat transfer agent into the secondary loop through a faulty generator, the sensitive gas radiometer will register a certain insignificant gas activity. In practice, it is always present in the primary loop, even with completely sound heating elements due to the presence of uranium traces on the outer surface of the shells. This is an unavoidable consequence of their manufacture at the factory (experience shows that there is always about 10^{-6}-10^{-7} g of uranium per cm^2 of surface area). The most dangerous case is when as a result of a faulty primary-loop seal there is a leak directly into the reactor compartment and through the steam generators into the secondary-loop steam.

The evaporating heat transfer agent contaminates the reactor compartment air. For this reason, control of the air is usually conducted in compartments which are most dangerous from the standpoint of the emergence of activity. In particular, such compartments are those in which all of the automatic reactor control equipment is installed, inasmuch as it is here that most of the reactor outputs are located. The task consists in being able to register the specific activity of the air as a result of leaks less than the average MPC, equal to about 10^{-9} curies/liter. Upon emergence of the active heat transfer agent into the steam of the second loop, when the activity is largely due to radioactive isotopes of the noble gases (xenon and krypton) and iodine, it is found convenient to maintain control by measuring the activity of the steam-air mixture of the turboaggregate condensers operating on the secondary-loop steam. Here it is possible to monitor even a small leak of a fraction of a leter per hour, which increases the activity of secondary-loop steam to a level on the order of 10^{-8} curie/liter. The usual leakage into the compartment air is 1.5-2% on the average of the steam output of the installation; this gives an average value of 10^{-9}-10^{-10} curie/liter, taking dilution into account. This is considerably lower than the corresponding MPC. Consequently, in the presence of proper dosimetric control, even with a coincidence of heating-element and steam generator malfunctions, it is possible to prevent the MPC in the air of service compartments from being exceeded by shutting down the malfunctioning steam generator.

Gas beta radiometers are used for controlling the air and the steam-air mixture; their pickups are installed in the ventilation ducts of all types.

As a result of the examination of the radiation environment under conditions of emergency operation, it is possible to conclude that:

a) breakage of the heating element shell seals leads in itself to a sharp and lingering increase in the heat transfer agent activity and higher activity of air in the reactor compartments; however, there is no direct danger to the operating personnel beyond the confines of the radiation shielding. There is a pre-emergency state when it is necessary to diagnose the malfunctioning reactor and not permit its prolonged exploitation;

b) the most serious case involves the emergence of fission fragments into the usually inactive steam of the secondary loop. This leads to their appearnace in the air of the regular service compartments, as well as an increase in the gamma radiation dosage beyond the limits of radiation shielding. In this case, dosimetric monitors must rapidly ascertain the presence of an emergency, determining the malfunctioning steam generator and making possible its immediate shutdown. The MPC will not be exceeded if the trouble is

noted in time. The likelihood of such a simultaneous breakdown of the heating elements and steam generator is not great. In principle, however, it can occur, and must be taken into account in advance;

c) particularly important is the insulation of the entire complex of compartments in the reactor section from the other ship compartments. This can be achieved by the full hermetic sealing of the radiation shielding, the outer contour of the entire reactor section, as well as the ventilation ducts leading from it, with the exception of their outside vents.

Radioactive Washdown and Deactivation Waters

During the operation of an NPP vessel, there is an unavoidable accumulation of radioactive wastes, which requires special means of collecting, controlling, and retaining them until further processing. All radioactive waters temporarily collected on nuclear vessels fall into the following categories:

a) waters of high specific activity -- the heat transfer agent of the primary loop and various undiluted leakages therefrom.

b) waters of low specific activity formed as a result of the deactivation of compartments, equipment, clothing, and personnel.

High- and low-activity waters must be kept in separate vessels, which facilitates their treatment and removal from the ship.

The specific activity of sewage and washdown waters is as a rule determined by the radioactive isotopes with long half-lives.

Highly-active water, upon exploitation of NPP with hermetically-sealed heating elements has a specific activity which usually does not exceed 10^{-2}-10^{-3} curie/liter. Weakly-active water, with a specific activity not exceeding 10^{-5}-10^{-6} curies/liter can be diluted with sea water down to 10^{-9} curie/liter and dumped overboard with the proper precautions. In practice, a leakage of 1 liter in several hours, constituting 0.01% of the average volume of the primary loop of 10 m^3 capacity is quite realistic. Taking the least specific activity of the washed-down and drained leakage equal to 10^{-5} curie/liter, and taking into account the required dilution down to 10^{-9} curie/liter, we already have 10 tons of weakly-active water. Usually before active waters are piped into the ship's tanks they are filtered through ion-exchange filters, which lowers the specific activity several orders. [Note: According to the sanitary regulations of 1957, the figure of 10^{-9} curies/liter is the MPC of strontium-90 in drinking water].

For collecting radioactive waters temporarily, nuclear vessels must be equipped with special storage and drainage tanks and drainage systems with the necessary pumps, pipes, and fixtures. Tanks for highly-active water must be enclosed in shielding. Weakly-radioactive water tanks need not be shielded. All active waters can be a source for the spread of radiation over the ship. For this reason, tanks for the collection of water, as well as the piping, pumps, and fixtures must be hermetically sealed and have the shortest possible length with a minimum number of joints. The drainage piping must not pass through living or service compartments. This is not difficult to realize in practice, inasmuch as they are usually localized in the reactor sectors.

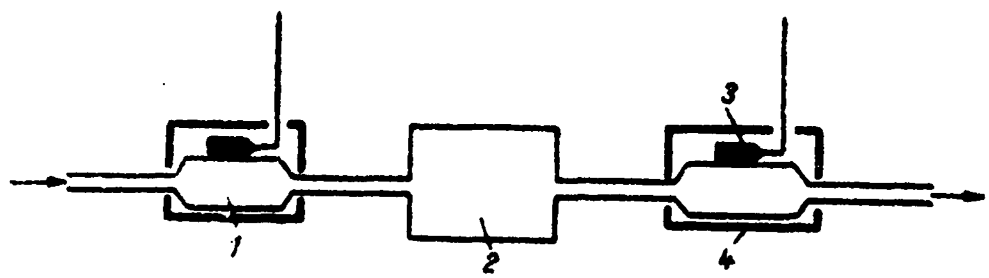

Figure 30. Schematic diagram of piping and pickups for measuring specific water activity. 1 -- widening of pipeline (counting space);2 -- filter; 3 -- radiometer pickup; 4 -- shielding screen.

The necessity of constructing shielding from gamma radiation from liquid wastes os determined by calculation for each specific case on the basis of the maximum possible initial activity. The drainage tanks must be removed as far as possible from the living quarters; they are best located in the space between bottoms under the reactor section.

The activity of drainage and deactivation waters is determined according to their gamma radiation, inasmuch as in a number of practically-significant cases the ratio between gamma and beta radiation is more or less constant. The gamma dosimeter pickups should be installed before and after the ion-exchange filters in special wide spaces in the piping (Fig 30) which are the counting spaces. Such a steup makes it possible, in addition to measuring the water activity, to control the effectiveness of the filter itself.

In the presence of significant gamma backgrounds, the pickup is usually enclosed in a special lead or steel screen whose thickness is calculated depending on the strength of the background and measured gamma radiation.

17. Problems of Radioactivity Localization on a Ship With a NPP

In planning and constructing stationary land nuclear installations, it is no trouble to isolate the reactor and auxiliary facilities capable of being contaminated with radioactive materials. They can be built in separate blocks which are fully isolated from the living and service quarters. It is much more difficult to do this in designing a nuclear vessel.

A ship, especially a large one, is a complex engineering structure, and its overall structure is subject to specific, purely marine, requirements which may come into contradiction with the requirements of radiation safety stemming from the presence of a nuclear plant. But it is obvious that under all conditions the arrangement of compartments in a nuclear vessel must assure that the personnel remain in sections where the level of total radiation emitted by the NPP is close to normal background. In the watch areas, the radiation level much be such that the total dose per watch does not exceed the maximum value, i.e., 0.005 reb or 0.1 of the maximum permissible dose of occupational irradiation. The possible concentrations of radioactive gases and aerosols in living and service compartments must not as a rule exceed the appropriate MPC. In planning radiation protection, it should always be borne in mind that the development of biophysics and biochemistry confirms the tendency toward the constant lowering of maximum permissible levels of irradiation and MPC. Radiation protection must be calculated with a certain reserve.

Along with the necessity for more rational arrangement of radioactively "clean" and "dirty" areas, it is of great importance to localize radioactivity within the reactor section, within the confines of "dirty" compartments. This is done by the hermetic sealing of the reactor section as a whole, the sealing of individual dangerous cubicles, as well as the creation of additional air pressures outside, or rarefaction within, the reactor section.

The hermetic sealing of the entire NPP is condition-classified as follows from the design standpoint:

a) primary technological loop;
b) auxiliary systems;
c) radiation shielding;
d) complex of reactor-section compartments.

Hermetic Sealing of Primary Technological Loop

To assure the best possible degree of hermetic sealing in all structures constituting the primary loop, the attempt is made to have a minimum number of joints of any type, especially flanged ones. The joints should be mostly welded with careful control over welding quality and all types of reinforcements. The methods of structural elements and welding, as well as the testing methods are specially worked out with due regard for working parameters -- temperature, pressure, and structural-design data.

Increased attention to structural-design details is due to the complicated operation of primary-loop structures under rapidly changing conditions as a result of the rapid variation of temperature fields during operations involved in the increase and decrease of reactor power. In particular, in water-water reactors, the structures and system of the primary loop operate under very difficult conditions -- at a pressure of about 200 atmospheres and a temperature from 300 to 350°C. During reactor operation (during power regulation), the heat transfer agent temperature varies within the limits of about 100 degrees, which complicates the conditions for the operation of structures still further. Particular attention is paid to the design of the heat exchangers, inasmuch it is they which can be the basic sources of serious radioactive contamination of the secondary loop under emergency conditions.

Hermetic Sealing of Auxiliary Systems

Among the auxiliary systems are the following:

rarefaction of air within the reactor section;

ventilation of reactor section and auxiliary compartments which may be contaminated with radioactive substances;

drainage and circulation systems for the sewage, deactivation, and washdown radioactive waters;

systems for circulating the heat transfer agent in the primary loop;

liquid deactivation systems, etc.

The importance of hermetic sealing from the standpoint of maintaining radiation safety of the ship does not require proof.

Special attention is also drawn here to the execution of all of these systems with the shortest possible length and the fewest fixtures possible (valves, spigots, etc.).

Hermetic Sealing of Radiation Shielding

Radiation shielding is usually a completely closed surface which excludes the possibility of penetration of radioactive substances beyond its limits and lowers the intensity of rays down to the lowest possible levels.

However, the piping of all types extending beyond the shielding -- steam pipes (secondary loop), water and auxiliary piping, drainage pipes, various ventilation ducts, cables, mechanical drive systems etc. -- unavoidably disrupt the closed surface, creating a large number of crevices through which gases and aerosols can escape. On the other hand, such weak spots can be points of escape for gamma ray beams. The first difficulty can be solved successfully by employing high-quality seals and maintaining air rarefaction within the biological shielding. The escape of gamma rays through crvices can be combatted by using non-straight shapes for the communication channels (Fig 31). The use of such irregular channels of zigzag or curved shape provides an adequate solution to the problem.

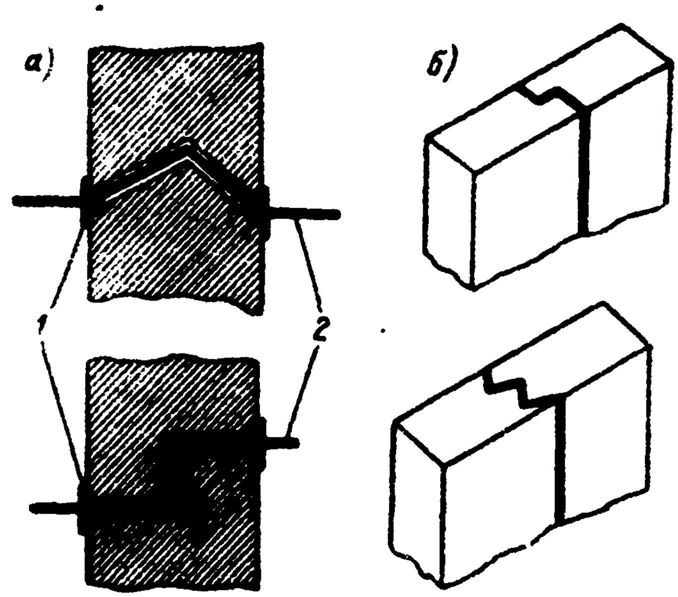

Figure 31. Diagram of cable or pipe channels in radiation shielding and shielding plate joints: a -- sketch of cable channel in radiometric shielding: b -- sketch of slitless plate joining for radiation shielding; 1 -- packing; 2 -- pipe or cable.

In practice, it is very difficult to realize complete hermetic sealing of radiation shielding and the entire reactor section. In connection with this fact, the localization of radioactive gases and aerosols can be reliably conducted through the creation of artificial air rarefaction within the reactor section and the use of special ventilation systems which eject the contaminated air after passing it through aerosol filters. Rarefaction on the order of about 50 mm of water is already quite sufficient for assuring the impermeability of the reactor section by gases, even taking into account possible gas diffusion.

It is necessary to point out once again that the structures of the rarefaction ventilation system, i.e., the ventilation ducts, ventilators, and fixtures must be hermetic over their entire extent, all the way to the point of air ejection into the outer atmosphere. It is advisable to concentrate all ventilators serving the reactor section in special hermetic enclosures, placing the latter within the reactor section. This measure is also important in the localization of possible escaping radioactivity. The ejection of contaminated air must be at the greatest possible height in order that the required diffusion and lowering of final activity concentration might be assured even without taking into account the effect of wind and the ship's motion. In practice, a height of about 20 m over the deck of the ship is adequate. The hollow masts may be used to advantage for this purpose. There must be constant remote control of air rarefaction in the reactor section. This is maintained from the dosimetric station.

The dosimeter pickups for controlling the activity of air sucket out from the reactor section are installed before and in front of the aerosol filters. This makes it possible to check on filter operation.

In the event of ejection of considerable aerosol activity (under emergency conditions) and unfavorable meteorological conditions, it is possible to have suck-in of the radioactive air into the living quarters through the receiving ducts of the ventilation system. Such a case is possible only in the event of a coincidence of a number of factors, which is generally rather improbable but still possible. However, despite the fact that the concentration of radioactivity in the incoming air is less than that of air ejected from the reactor section by at least two orders of magnitude, the amount of incoming air must be strictly controlled with the aid of appropriate equipment for gas and aerosol control. The pickups are best installed in the air intake vents.

Hermetic Sealing of Ducts Leading From and To the Reactor Section

In addition to the spread of activity over the ship along with the air, it can also cling to the clothing, shoes, and bodies of the service personnel and carried out in this way from the reactor section. In order to prevent this, the exit from the reactor section leads through a special sanitary locker and shower compartment. This block must be equipped with radiometers to monitor the cleanliness of bodies and clothing, as well as deactivation quality. Only upon total washing of radioactive matter from the body can the personnel leave the reactor section after changing into clean clothes and receiving permission from a radiation monitor.

The control over radiation-free cleanliness of clothing, shoes, and body must be strictly maintained, since the detection and deactivation of radioactivity once it is spread over the ship is very difficult and complex.

The deactivation laundry facilities must also be in the reactor section for safety purposes.

18. Formulation of the Problem of Removing Nuclear Fuel Fission Fragments from Nuclear Vessels

Due to the long half-life and high degree of activity of certain fission fragments, the problem of their collection, storage, and removal from nuclear vessels assumes great importance. In particular, to evaluate the degree of contamination of the heat transfer agent in the water-water reactor by such radioactive materials and their half-lives, it is possible to use the interesting results of radiochemical and radiochemical analyses carried out in the study of the heat transfer agent at the first Soviet atomic electric power station. Water samples were taken ahead and in front of the filters in the primary technological loop; these were measured for beta activity. Then, with the aid of a radiometric analysis of the fragment decay curves, a determination was made of the radioactive components.

The measurements showed that with undamaged heating elements, the specific activity of water fluctuated about the value $5 \cdot 10^{-5}$ curie/liter . The analytic data showed that the radioactive water in the first loop prior to filtration in the ion-exchange filters has six components with the following average half-lives: 2.5 hours, 15 hours; 26.5 days, 42 days, over 100 days, and over 5 years. The filtered radioactive water contains only the first four components, i.e., the highest half-life is 42 days.

The subsequent chemical and other tests showed that the water heat transfer agent contained sodium, calcium, iron,

copper, nickel, cobalt, manganese, chromium, and silicon. This contamination of primary-loop water is mainly due to the products washed down with the water (erosion and corrosion products) from the inner surfaces of the metal pipes and structures of the primary loop, as well as (to a smaller degree), as the result of the presence of impurities in the feedwater, even with a high degree of purification. It can be assumed that the quantity of corrosion products from primary loop structures increases in time due to the fact that some quantity of nitric acid forms in the loop as a result of the oxidation of nitrogen dissolved in the water.

In the case of heating element shell washout, the radioactivity of the heat transfer agent increases sharply (up to 10^{-1} curie/liter and over), and it exhibits a high content of radioactive isotopes with long half-lives (up to several years). All of this is especially dangerous in the drainage and storage of the primary-loop heat transfer agent in special tanks for weakening and further processing.

The task of removing radioactive wastes from nuclear vessels can be solved in approximately the following ways: The active water must be piped into specially-equipped tanks surrounded by the required shielding. There the water is kept to allow for the weakening of activity through the decay of short-half-life isotopes. After this, the remaining long-half-life radioactive materials along with the used agent from ion-exchange and other agents are conveyed to special floating or shore bases for purification and treatment, including special measures for the burial of concentrated radioactive residue in hermetic containers in special burial grounds. It is also possible to dilute radioactive waters with sea water down to an activity level established by international regulations for drinking water and subsequent dumping overboard in areas remote from inhabited shores and fishing waters. However, taking into account the fact that the dumping of even strongly-diluted wastes increases the total activity of the seas, which is not desirable in the final analysis, this method must be deemed unsatisfactory from the long-term standpoint of keeping the world ocean pure.

It is to be assumed that the further elaboration of this problem will bring about the maximum reduction of the quantity of removed radioactive wastes. In particular, the heat transfer agent should be returned to the primary loop for reuse upon purification.

In an analogous manner, it is likely that methods will be developed for the filtration and concentration of radioactive gases, which will make it possible to ventilate the reactor section in a closed cycle.

As a result, nuclear vessels will simply have to remove concentrated radioactive wastes and replace the filter elements, which will considerably simplify the assurance of radiation safety.

At the present time, the problems of the technology of removing, purifying, and storage of NPP wastes are still in the stage of solution, so that we could only deal briefly with these problems in a preliminary discussion.

Chapter VI

ORGANIZATION OF THE DOSIMETRY SERVICE ON SHIPS WITH NPP

19. General Remarks

In this chapter we shall attempt to present in an organizational-technical framework the problem of the dosimetry service on nuclear vessels which has as yet had no practical elaboration; what we have to say is therefore open to criticism and correction. The entire subject-matter is presented in the form of a formulation of the question.

In the construction, testing, and exploitation of nuclear vessels, radiation safety must be assured to both the service personnel of the ship and the people in the vicinity of the ship either at sea or on shore (during docking). The organization of radiation safety procedures can only be assured provided the ship has a special dosimetry service.

The dosimetry service must be set up in order to assure timely detection of dangerous radioactive contamination and streams of penetrating radiation, the taking of proper safety measures, and the liquidation of emergency conditions in volving the NPP.

For the purpose of controlling crew safety, the dosimetry service must fulfill the following tasks:

a) the assurance of control over the irradiation of the personnel with ionizing radiation from the NPP;

b) the assurance of control over gamma-ray intensity and neutron intensity from the NPP and the degree of radioactive contamination of air, water, compartments and equipment surfaces, as well as clothing, edibles, drinking and bathing water, etc.

c) timely qualitative discovery and quantitative analysis of abnormalities in NPP operation accompanied by a rise in ship radioactivity above maximum permissible values and MPC of gases and aerosols over the normal NPP operation regime;

d) control over the radiation state of water in the vicinity of the ship and the surrounding air upon the disruption of normal NPP operating conditions.

20. A Sample Organizational Scheme for a Dosimetry Service

To fulfill the tasks set out for it, a dosimetry service must do the following:

1) maintain constant surveillance over the radiation state of the ship with the aid of continuous control over the levels of penetrating radiation, aerosol and gas concentrations, and sporadic (periodic, if need be) control of radioactive contamination of ship compartments and equipment;

2) immediate determination of causes of increased radiation levels and excessive concentrations of radioactive gases and aerosols over permissible levels corresponding to the normal state of the NPP; issuance of instructions on measures to correct the situation and control over their fulfillment;

3) control of irradiation of ship personnel by NPP ionizing radiation;

4) control of the radioactive state of the water and steam used aboard ship for drinking, bathing, heating, air conditioning, etc., as well as food, in case of improper NPP operation accompanied by radioactive contamination of compartments outside the reactor section;

5) control over the fulfillment of rules for the removal of radioactive wastes from the ship -- the contaminated heat transfer agent from the primary loop, sewage and deactivation waters, as well as the degree of their purification or dilution;

6) traning of personnel in measures of radiation safety and work rules in the reactor section.

The system of dosimetric instruments on a nuclear vessel represents a single complex. Somewhat arbitrarily, however, they can be broken down into two parts: instruments for so-called technological and biological dosimetry; the latter are of a subordinate character.

The instruments for technological dosimetry are intended for radiation control of reactors and NPP loops. They must send out signals in the case of a broken seal in one of the loops, the reactor blocks, the appearance of heat transfer agent leakage, etc., and aid in the determination of causes and concrete sources of radioactive contamination of air and water aboard ship.

Biological dosimeters are used to control the radiation environment only in the compartments where the personnel remain permanently. It should be borne in mind that the appearance of an intensified gamma background, gas activity, etc., indicates NPP malfunction, and the operator has an additional means for its detection. In this consists the subordination of the biological dosimetry system, because of which the indicates division is purely arbitrary.

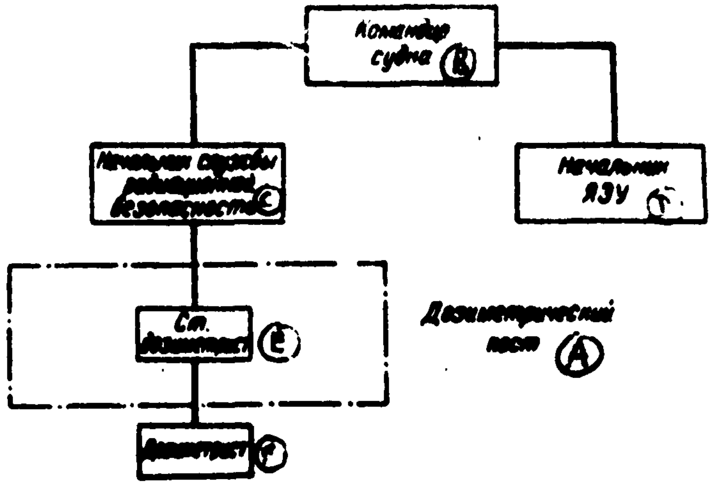

Figure 32. Skeleton scheme of radiation safety service (RSS) organization. A = Dosimetry watch; B = Captain of vessel; C = Head of radiation safety service; D = NPP head; E = Chief dosimetrist; F = Dosimetrist.

At the disposal of the dosimetry service there may be stationary dosimetric devices of the continuous-operation type which assure remote control and the measurement of the levels of all types of radiation, as well as a number of portable dosimeters and personal dosimetric control devices. All signalling-measuring blocks of dosimetric apparatus should be concentrated at the dosimetry watch station (a separate, specially-equipped compartment). The work connected with the exploitation of dosimeters is performed only by the specially-trained personnel of the dosimetry service. The size of the staff depends on the special features of ship NPP equipment, as well as the quantity and complexity of apparatus.

The chief of the radiation safety team should be responsible directly to the captain along with the person responsible for the operation of the reactor section (or the entire NPP), inasmuch as the radiation state of the ship is one of the important factors determining the technical possibility of NPP exploitation.

A possible skeleton scheme for the organization of a radiation safety service is given in Fig 32.

The functions of the dosimetry service consist of NPP control determined at a given time by its technical state, as well as daily maintenance of dosimetric equipment.

It is possible to have the following regimes of dosimetry service work:

1) normal; when the ship with a normally-operating NPP is either at sea or in port;

2) emergency; when NPP malfunctions are being eliminated;

3) docking; when the vessel is in port with the NPP shut down.

There can also be a regime of dosimetry service work while heating elements are being replaced, the primary loop washed out, the used heat transfer agent is being replaced, during dock maintenance operations, etc. These regimes which are specific in nature and as a rule carried out with the aid of the shore dosimetry service, will not be considered here.

21. Skeleton Scheme for Dosimetry Control and Signalization

A typical dosimetry control system for all vessels in general cannot be suggested because its structure is greatly dependent on the concrete nature of the NPP and the ship as a whole. Let us state this more clearly.

The basic task of the dosimetry system as stated above consists in the assurance of radiation safety of the personnel of a nuclear vessel through the control of ionizing radiation and the proper operation of NPP elements -- first and foremost the reactors and technological loops and related equipment. These tasks on the whole determine the organization of dosimetric control services. The types of controlled radiation and measurement ranges are likewise chiefly determined by the designand characteristics of ship reactors, loops, radiation shielding, and overall arrangement of compartments.

The following requirements have to be met by the dosimetry control system:

1) it must be centralized. Indeed, dosimetric control data must be channeled to the single dosimetry station in order that the operator on watch (the dosimetrist) might quickly generalize them for various types of control and evaluate the radiation state of the ship as a whole;

2) dosimetric control must assure the service personnel not only the possibility of rapid orientation in the radiation environment aboard ship, but also indicate the concrete causes and locations of malfunctions producing its variations;

3) the organization of dosimetric control must be integrated with the overall NPP control organization, i.e., with the quantity, purpose, and location of ship and NPP control posts -- in the section where the equipment for signal reproduction and ship intercommunications between control posts is located.

NPP control presupposes maximal automation, in which all of the basic control operations can be carried on from a

single central station. Let us call this the power control station (PCS). This station is the center for all remote-control apparatus for the reactors and auxiliary mechanisms -- control panels for starting up, regulating, and shutting down the NPP, signalling devices and communications equipment of all types, as well as dosimeters. At the present time, wide use is being made of mnemonic control panel layouts showing the block diagrams of technological and auxiliary NPP loops with indications as to the control points and regulatory organs. Such designs assure convenience and at-a-glance control.

The dosimetric control system should be structured in a similar way. This will first of all facilitate trouble-spotting in the NPP and technological loops, and will also assure effective control of the radiation environment on the ship as a whole.

In dosimetric control systems onnuclear vessels, most of the dosimetric equipment is stationary. Portable devices are used to supplement the stationary dosimeters in the event of malfunction, to monitor radiation in usually unmonitored areas, as well as to check on the contamination of removable structures (e.g. trapdoors, etc.).

On auxiliary base ships which service nuclear vessels and used for the transsport, purification, storage, and removal of radioactive wastes, the inclusion of stationary dosimeters is not always mandatory. This considerably simplifies the dosimetric system and increases the role of portable instruments.

Taking into account the requirements of centralized dosimetric control which stem from the specificity of conditions and the considerable complexity of equipment, it is advisable to set up the dosimetry station in a separate compartment, including only the necessary duplicate signalling devices on the PCS control panels. It may likewise be necessary to place control apparatus on the dosimetry control panel which indicate the regime of NPP operation at a given moment. This will allow the dosimetrist to make a more precise estimate in an emergency situation.

Fig 33 shows a sample diagram of one channel of a dosimetric installation. The diagram is simple enough and does not require additional explanation. However, it is necessary to say something about the system of "threshold" signalling. Practice has shown it convenient that it is convenient to have the dosimetric equipment send out signals fixing specific radiation levels (thresholds), e.g., the permissible, maximum, and dangerous levels (the latter two for an emergency NPP operating regime). Such a stepwise signalling scheme aids the dosimetrist in rapidly assessing the radiation environment. This signalization should be placed on the main control panel in the dosimetry station, and the NPP and PCS control panels and the entrances to

the monitored compartments. Each fixed radiation level must have its own signal light which would light up at the central dosimetry station. For example, it is possible to have the following system of colored lights: green permissible radiation level; yellow -- maximum permissible level of radiation; red -- dangerous radiation level; blue -- dangerous concentration of radioactive gases and isotopes.

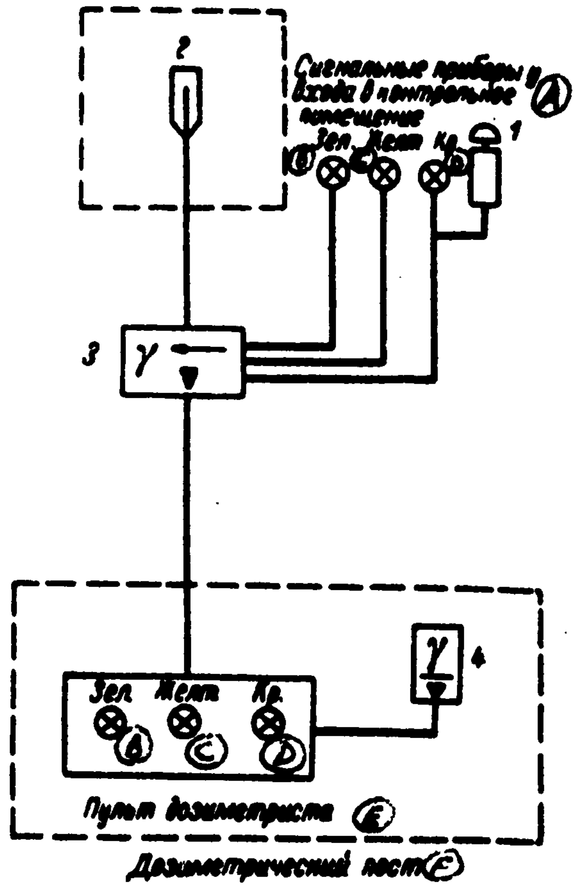

Figure 33. Diagram of one channel of a dosimetric facility. 1 -- Bell; 2 -- Pickup; 3 -- Intermediate indicating instrument; 4 -- Dosimeter measuring instrument. A = Special devices at entrance to controlled compartment; B = Green; C = Yellow; D = Red; E = Dosimetrist's control panel; F = Dosimetry station.

The use of such colored signals on display and control panels in combination with the NPP mnemonic layout assures a sufficiently clear assessment of the radiation environment on the ship. The appearance of danger signals for radiation of all types should be combined with audible

signals (buzzers, sirens, bells) to draw the operator's attention. In planning the signal systems, the signalling instruments should be made quite distinct with respect to color and sound. Relay devices grouped in special relay boxes or on panels can be used for the switching and commutation of color and sound signalling devices at the electronic circuit outputs. The basic scheme of a relay signalling hookup (Fig 34) is simple and needs no special explanation.

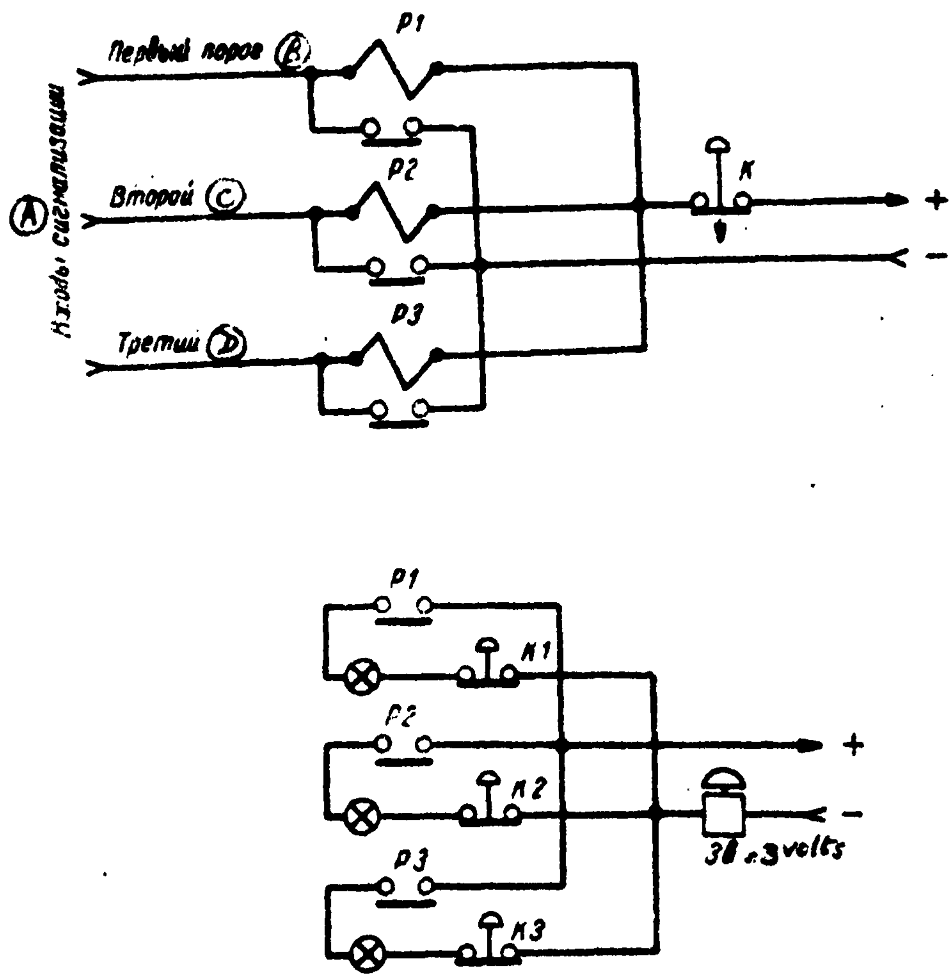

Figure 34. Basic signalling scheme.
K -- General triggering button; K1, K2, K3 -- Signal triggering buttons; P1, P2, P3 -- Trheshold signalling relays. A = Signal inputs B, C, D -- 1st, 2d, 3rd thresholds, respectively.

It is merely necessary to note that the device circuit has its own separate output for each signal line (green, yellow, red, and blue), or assures selectivity upon linkup with the corresponding repeater relays P1, P2, etc.

Fig 35 shows a sample basic dosimetric control scheme for a hypothetical nuclear vessel. This scheme is by no means exhaustively complete. It was conceived with no specific vessel in mind, but is intended merely to give a clear a conception as possible of the dosimetric system as a whole. The scheme includes the basic measurement and signalling apparatus and shows the points where pickups and secondary dosimeters are installed. For the sake of completeness, it is assumed that the ship has both a central PCS (power control station) and a reserve power control station (RPCS).

The pickups are grouped according to the types of monitored radiation; it gives the name of the compartment or mechanism on which they are installed, as well as the coordinates of the installation point -- deck, bulkhead, strake. The dosimetry station panel has only the colored signal lights; the secondary instruments can be installed on any of the nearby partitions. Upon actuation of the signal, the dosimetrist comes to the appropriate direct-reading instrument and takes his data.

This is accompanied by the triggering of the analogous color signals on the NPP control panels in the PCS and RPCS. The sound signals should not be installed in the PCS and RPCS, because and excessive abundance of sound signals at these stations can hinder the basic functions of the operators on duty.

In the presence of multi-channel dosimeters, it may be convenient to employ a single central block containing all measurement channels. Such a block has a single measurement device which is switched to the selected pickup channel, as shown in Fig 35 for the case of measurement of the activity of the primary heat transfer agent with respect to gamma emission. The use of such multi-channel will considerably simplify the scheme shown in the figure and reduce the amount of equipment in the dosimetry station. At times, according to conditions of NPP exploitation and depending on overall ship design, it may be expedient to install color signals and even duplicate measurement instruments at the entrances to certain of the reactor section compartments. This is not shown in Fig 35. Also left out is the entire relay-commutation apparatus -- connector post boxes, relay boxes, etc.

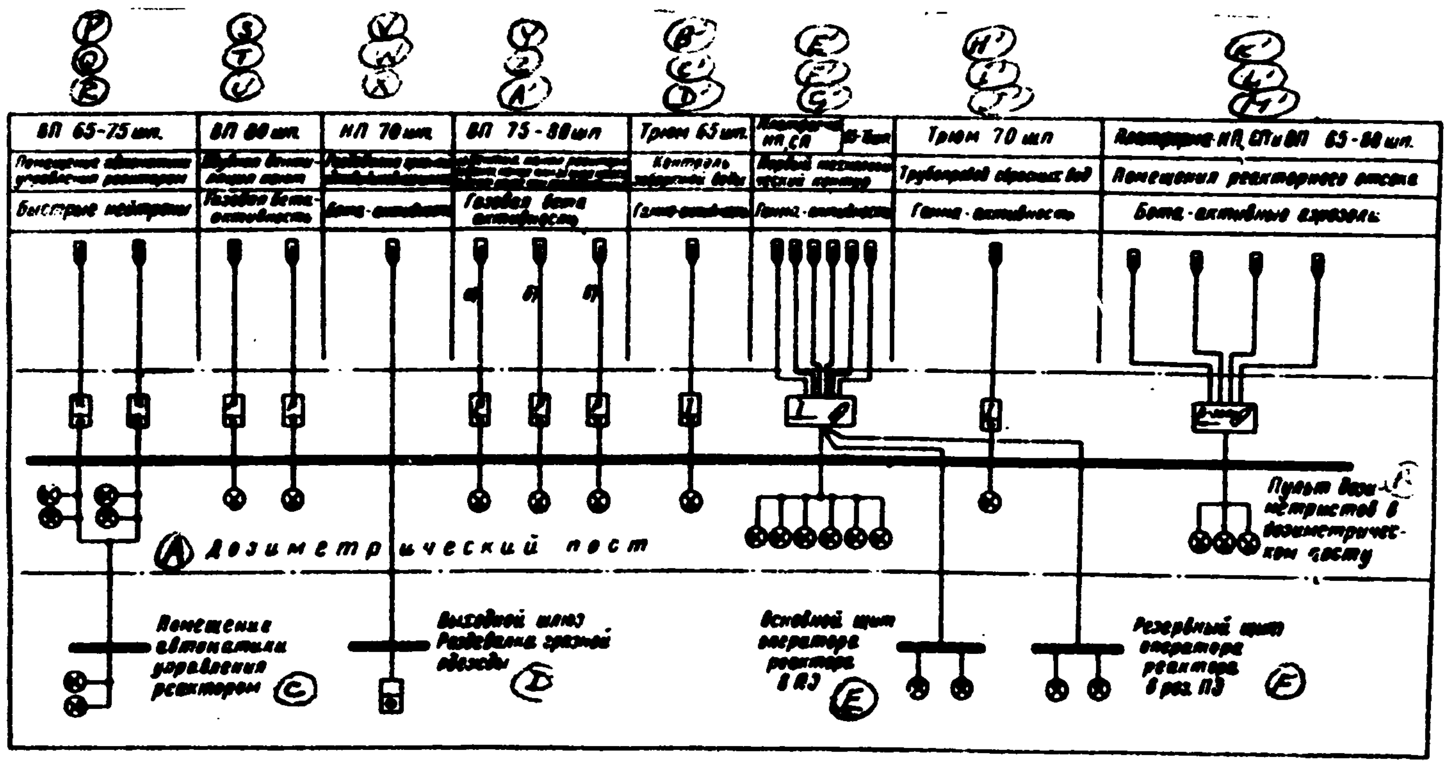

Рис. 35 Примерная принципиальная схема дозиметрического контроля судна с ЯЭУ.

(G) — сигнальная лампа желтая;
(H) — » » синяя;
(I) — » » зеленая;
(J) — » » красная;
(K) — вторичный прибор дозиметра или радиометра (показ и сигнал местный);
(L) — то же (показывает с переключением датчиков);
(M) — то же (сигнализирующий);
(N) — то же (показывающий и сигнализирующий);
(O) — датчик дозиметра или радиометра.

Figure 35. Sample basic scheme of dosimetric control system for a nuclear vessel. [See legend next page].

[Figure 35. Legend]:

A = Dosimetry station; B = Dosimetrists' panel in dosimetry station; C = Compartment containing automatic reactor control equipment; D = Exit and dressing room (dirty clothes removal); E = Main control panel in PCS; F = Reserve control panel in RPCS; G = Yellow signal light; H = Blue signal light; I = Green signal light; J = Red signal light; K = Secondary dosimeter or radiometer device (local signal and device); L = Same as K (display with pickup switching); M = Same (signalling); N = Same (display and signalling); O = Dosimeter or radiometer pickup; P = Upper deck, 65-75 blkhd; Q = Compartment containing automatic reactor control equipment; R = Fast neutrons; S = Upper deck, 80 blkhd; T = Cabin ventilation (blowin); U = Gas beta activity; V = Lower deck, 70 blkhd; W = Exit dressing room; X = Beta activity; Y = Upper deck, 75-80 blkhd; Z = a) reactor ventilation channel, b) ventilation channel behind circulation pump, c) heat exchanger compartment ventilation channel; A' = Gas beta activity; B' = Hold, 65 blkhd; C' = Sea water control; D' = Gamma activity; E' = Lower deck-Middle deck platform, 65-75 blkhd; F' = Primary technological loop; G' = Gamma activity; H' = Hold, 70 blkhd; I' = Sewage water plumbing; J' = Gamma activity; K' = Lower, middle, and upper deck platform, 65-80 blkhd; L' = Reactor section compartments; M' = Beta-active aerosols.

22. Placement of Dosimetry Apparatus

As was already pointed out above, the assurance of radiation safety on a nuclear vessel is one of the most important problems in design which significantly affects the general arrangement of ship compartments and the design of the reactor section. In this connection, the determination of points for the installation of pickups and devices for the dosimetric control system is likewise of first-rank importance. Below we attempt to convey some idea of the placement of dosimetric apparatus.

Inasmuch as design peculiarities in the distribution of dosimetric instruments are primarily contingent on their purpose (type of radiation or activity to be monitores), the discussion below does not take into account the arbitrary division of dosimetry into technological and biological monitoring.

Stationary Ship Facilities for Controlling Gamma Radiation and Portable R-Meters

R-meters. These are used to control:

gamma ray intensity beyond the confines of the radiation shielding;

the intensity of the external gamma field outside the ship [note: the pickups for controlling the external gamma field are not integral parts of nuclear vessel dosimetry, but their installation is desirable for the sake of completeness of information on ship radiation sources. For example, they register external gamma ray sources].

the possibility of emergence of the primary-loop heat transfer agent into the secondary NPP loop (leakage control) or into the reactor-section air;

specific activity of deactivation and sewage waters and ion-exchange filter operation [note: special studies showed that the fragment composition of radioactive water contaminations and the ratio of beta and gamma radiation are sufficiently stable. This has made it possible to adopt the method of controlling the specific activity of sewage waters according to the gamma radiation of the fission fragments ahead of and after the ion-exchange filters].

specific activity of sea water used in auxiliary-mechanism cooling systems.

Devices for measuring neutron streams. These devices are used to control streams of fast and thermal neutrons beyond the confines of radiation shielding and in the reactor area itself for the purpose of checking the neutron shielding.

Devices for controlling gas beta activity. These register the following:

the specific activity of air sucked out by the ventilation system from the reactor section or adjacent compartments appearing as a result of active gas leakage through various structural crevices in the NPP;

the appearance of gas activity in the secondary NPP loop due to disruption of heating-element and steam generator hermetic seals;

quality of air sucked by ventilation from the outside for ship compartments.

Beta radiometers. These devices are employed to control the radioactive contamination of equipment, deck surfaces, and compartment partitions, as well as skin surfaces and clothing of the service personnel.

Devices for controlling radioactive aerosols. These devices make it possible to control the appearance of radioactive aerosols as a result of primary-loop leakage, as well as of evaporation of sewage and deactivation waters.

The deployment of pickups is the basic problem in the distribution of dosimetric equipment aboard ship.

Let us consider the basic instances of dosimeter pickup distribution which depends largely on the selected control technique.

Principle for Deploying Stationary-Dosimeter Pickups for Controlling Gamma Radiation Levels

General-control pickups are placed by units in compartments adjacent to the reactor section.

Pickup installation points are chosen with respect to the distribution of the gamma field obtained from the calculation and construction of isodosal diagrams. The pickups are placed at points in the compartment, where, in accordance with the isodosal diagrams the gamma-ray intensity is maximum. Within the limits of calculation accuracy, the picture provided by isodosal diagrams confirms the pickup distribution.

The pickups for controlling the external gamma field should be places at high points on the superstructure or masts in such a way as to provide monitoring over a solid angle of 2π. Usually, two pickups, one to port and one to starboard, are sufficient.

The pickups which control the alteration of activity in the primary and secondary loops are installed on the appropriate pipes.

The pickups installed on the pipes and structures of the primary loop are mounted with the observance of the following conditions:

a) to avoid measurement errors, it is necessary to provide shielding from the external gamma background; for this reason, the pickup and the controlled portion of pipe or other structure are enclosed in a lead or steel enclosure of the required thickness;

b) if the pickup (mainly the detector) is not designed for constant operation under high-temperature conditions, it is necessary to cool it by any of the various means available (e.g., by flowing water).

A diagram of water-cooled pickup installation on a steam pipe appears in Fig 36.

Pickups for Controlling Primary-Loop Leakage

With respect to gas beta activity. Pickups are installed mainly to control and detect small leaks. They are mounted on the main lines which carry off the air-steam misture from the turbine condensers [see note], in the reactor section ventilator ducts, the special duct for carrying away air directly adjacent to the reactors, and the ventilation ducts carrying air from the surrounding atmosphere into the compartments. Radiometer pickups are installed in specially-packed portions of the ventilation ducts with definite dimensions calculated in advance which replace special counting enclosures (See Chapter 4, Sec 3).

[Note: The activity of the heat transfer agent (bidistillate) in the presence of an ion-exchange filter depends mainly on that of the gases. For this reason, a very effective means of controlling the presence of radioactivity in the secondary NPP loop is the method of measuring the activity of the air-steam mixture drawn off from the turboaggregate condensers by means of ejectors].

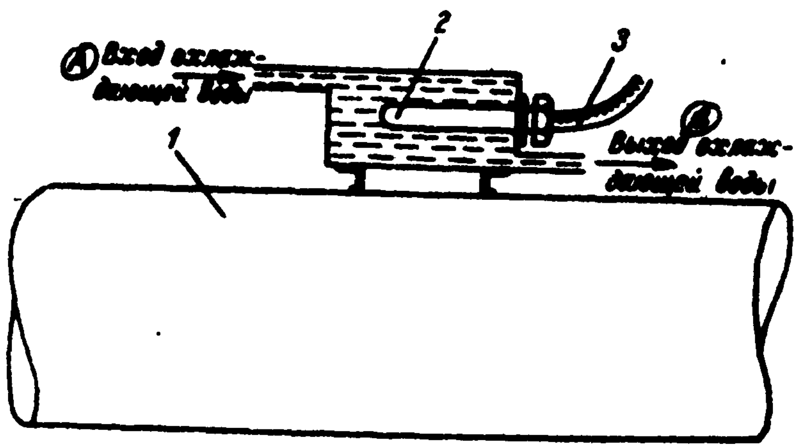

Figure 36. Sketch of water-cooled pickup mount on steam pipe. 1 -- Steam pipe with thermal insulation; 2 -- pickup; 3 -- cable; A = Water-coolant intake; B = Water-coolant takeoff.

If the calculated cross-section of the counting volume differs from that necessary for ventilation specifications, the latter is "blown up" in size at the necessary point.

A sketch of the mounting of a beta radiometer in the ventilation duct is shown in Fig 37.

With respect to aerosol activity. The pickups for controlling aerosol activity should be mounted in the same channels as the gas pickups, with the exception of the air-steam mixture pipes.

The centralized measurement of aerosols in several compartments can be performed with just a single pickup and a system of collection vents (Fig 38). In case of centralized collection of samples of air controlled with respect to specific aerosol activity, the entire complex of apparatus capable of being contaminated with active substances, i.e., the air blower, the air flow meter, remote-controlled valves,

and the pickup itself with its filter and detector should be installed in some compartment in the strict-regime zone within the reactor section. Most often, the ventilation cubicle which houses the ventilators serving the reactor section are located, serves this purpose. The organs of remote control over the valves and aerosol radiometer should be located at a central dosimetry station.

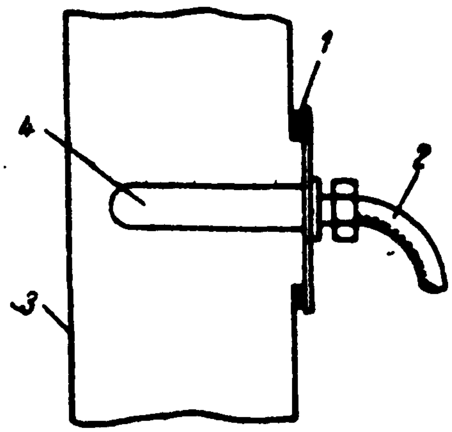

Figure 37. Sketch of gas beta radiometer mounting in ventilation duct. 1 -- packing; 2 -- cable; 3 -- ventilation duct; 4 -- pickup.

Portable Dosimeters

On a nuclear vessel, there must be compulsory periodic checks of the level of contamination of all reactor-section compartments, as well as other compartments under emergency conditions. Similar systematic checks must be carried out in the sanitation dressing room, dirty-clothes room, and special deactivation laundry. Depending on the results of the check, the indicated deactivation is carried out and instructions issued on the maximum length of presence in the various compartments.

For this purpose, the ship is equipped with portable dosimeters. These include:

1) r-meters with a range of gamma measurement from 10^{-1} to $15 \cdot 10^3$ microcuries/sec;

2) devices to measure fast and thermal neutrons with a measurement range from 3.0 to $3.0 \cdot 10^3$ neutrons/cm^{2}sec.;

3) beta-radiometers to measure surface contamination with a range from 1 to 10^6 events/sec$\cdot$cm^2;

4) set of individual control-measurement instruments for registering total radiation doses absorbed by personnel during duty hours.

All of the instruments must be transportable under ship conditions and have portable power supplies.

At the present time, such instruments are being built in the Soviet Union on a serial basis.

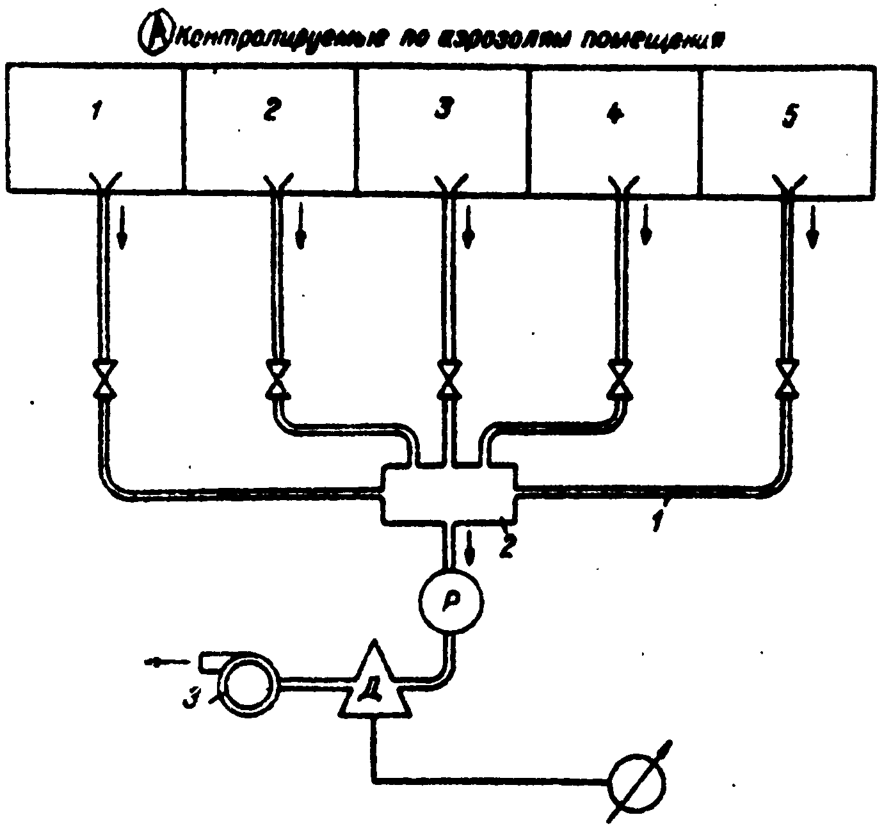

Figure 38. Diagram of system for measuring radioactive aerosol concentrations. 1 -- air ducts; 2 -- air collector; 3 -- air blower; Д -- radiometer pickup; P -- flow meter; ⧖ -- remote-operation electromagnetic valves. A = Compartments monitored for aerosol radioactivity.

The Iodine Radiometer

The personnel on the nuclear vessel must undergo periodic medical checks during which measurements are made of the iodine-131 accumulated by the thyroid gland; this makes it possible to judge the dose of radiation received from this emitter. The measurement is carried out with a special high-sensitivity radiometer which registers the gamma

radiation of iodine-131, starting from 0.02-0.04 microcurie, which is 5-10 times less than the maximum permissible content of this isotope in the human body. The instrument is installed in one of the medical-block compartments which should be as far removed as possible from the reactor section in order to reduce the gamma background.

23. The Dosimetry Watch Station and the Organization of Its Operations

The problems of the organization of dosimetry services on nuclear ships are new and have received no practical elaboration. For this reason, this section contains but an attempt to outline the basic factors in the possible organization of the work of the dosimetry watch station. It is not the purpose of this book to provide instructional materials to dosimetry service workers; but in order to understand the daily functions of the service, the section includes a list of the basic duties of members of the dosimetry service.

Above we already indicated the necessity for centralized dosimetry aboard ship. The dosimetry station (DS) must be this center. It should be located in the reactor-section area for the maximum possible curtailment of all entering ship communications -- pipes, cables, entrances, and exits. The DS must contain all apparatus for remote observation and control of the radiation environment aboard whip (direct-reading, recording, and signalling dosimeters), as well as intercommunications equipment (telephones, intercoms, and necessary signalization).

The DS should also have places for storing individual dosimeters, spare instruments and parts, control-measurement dosimeters, and portable dosimeters. If a nuclear vessel does not have a special area for maintenance work and calibration of dosimeters, the DS must have a special container with lead shielding for the storage of control and calibration samples. It is very desirable to have the BS compartment to be heat- and sound-insulated and diffused illumination to avoid sharp reflections from instrument scales and dimming of color-signal lights. A sample plan for a dosimetry station is shown in Fig 39. It was designed to assure radiation control with the aid of single-channel dosimetric installations.

If multi-channel dosimetric equipment is used, the floor plan of the dosimetry station is considerably simplified, since in place of a large number of secondary devices, it is necessary merely to install one or two multi-channel measuring-signalling devices. It is likewise more convenient to conduct observations and measurements because all of the control, signalling, and measuring equipment is easily mounted directly on the dosimetrist's panel. A block diagram of such a multi-channel system is shown in Fig 40.

Fig 41 shows a second variant for the floor plan when multi-channel equipment is to be installed.

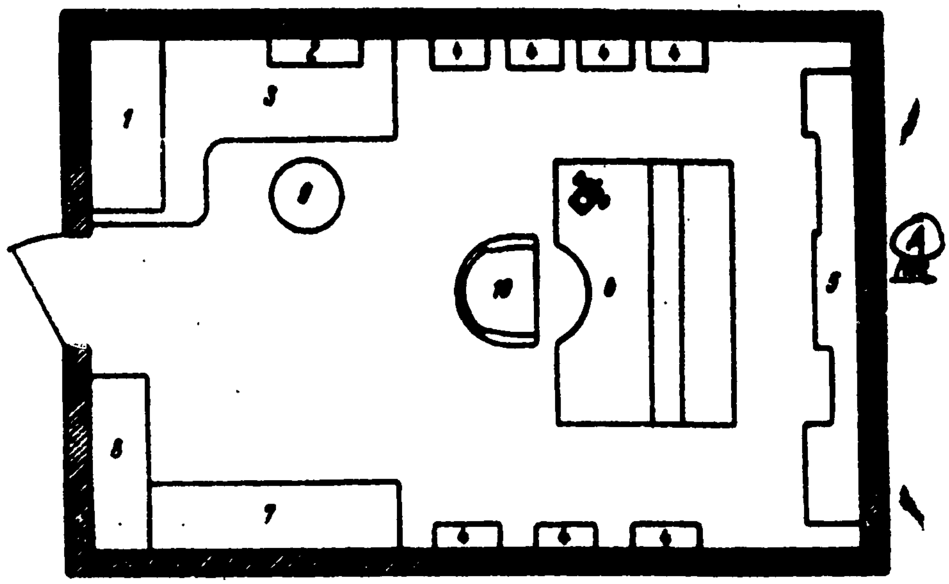

Figure 39. DS plan (1st variant).
1 -- Special cabinet with lead shielding for storing radioactive isotopes; 2 -- Electric panel; 3 -- Table for instrument repairs; 4 -- Secondary dosimeter and radiometer indicators; 5 -- Commutation appratus; 6 -- Dosimetrist's signal panel; 7 -- Cabinet for portable dosimeters; 8 -- Spare-parts rack; 9 -- Stool; 10 -- Armchair. A = Ship's bow.

Sample List of Duties of Dosimetry Service Staff

The dosimetry service of a nuclear vessel is independent, answerable directly to the captain, his senior assistant, or a person responsible for the radiation state of the ship as a whole.

The dosimetry service staff is responsible for the following:

1) proper organization of dosimetric control and assurance of radiation safety of the men aboard in accordance with the maximum permissible radiation doses;

2) timely and expert performance of radiation surveys and planned measurements of radiation levels and contamination of compartments and equipment, and concentrations of active gases and aerosols;

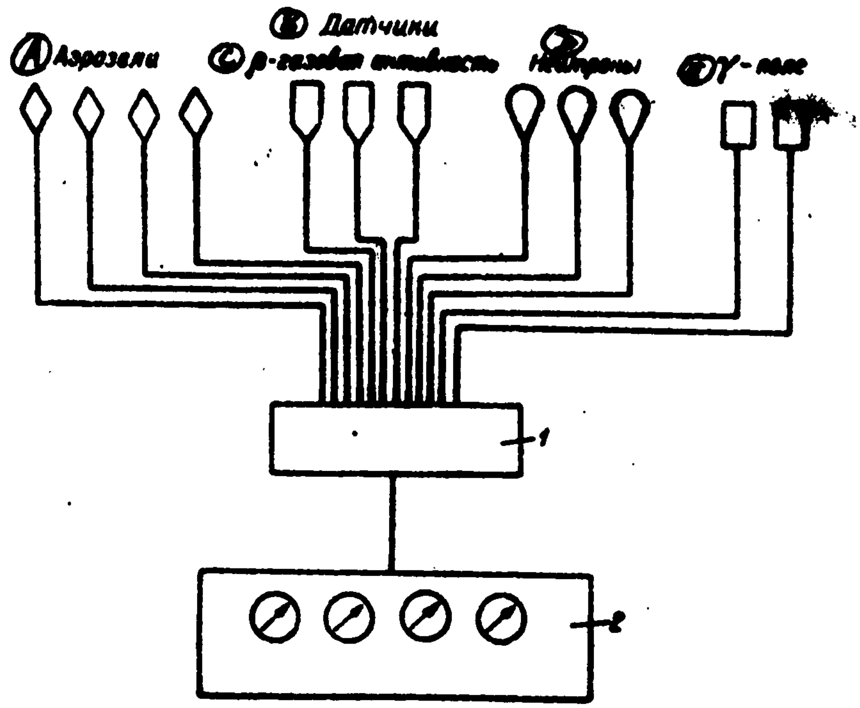

Figure 40. Skeleton scheme of "D" multi-channel system. 1 -- relay-commutation device; 2 -- central measurement panel. A = Aerosols; B = Pickups; C = β-gas activity; D = Neutrons; E = γ-field.

3) performance of dosimetric control functions in deactivation operations;

4) control over the fulfillment by the ship's personnel of measures to assure radiation safety in work under conditions of increased radiation levels, concentrations of radioactive gases and aerosols, as wellas radioactive contamination of ship compartments and equipment;

5) keeping the dosimetric instruments of the ship in good working order and in readiness;

6) organization of proper storage, maintenance, and replacement of dosimetric instruments and individual safety equipment;

7) training of personnel in the basic rules of radiation safety, use of individual dosimeters, and use of individual safety equipment;

8) training of personnel in deactivation of special clothing, equipment, and skin surfaces;

9) keeping of special logs containing all information on the activities of the service, irradiation doses absorbed by all persons working in the limited-presence zone, data on all types of dosimetric surveys, and the description of NPP malfunctions as well as measures for their elimination.

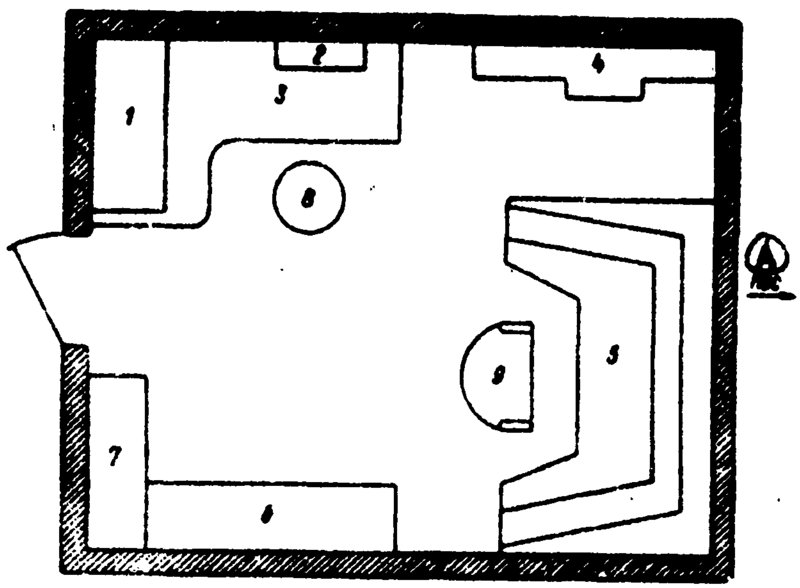

Figure 41. Central DS plan (2nd variant).
1 -- Special lead-shielded cabinet for storing radioactive isotopes; 2 -- Electrical panel; 3 -- Table for instrument maintenance; 4-- Relay-commutation equipment; 5 -- Dosimetrist's signal and measurement panel; 6 -- Cabinet for portable dosimetric and radiometric devices; 7 -- Spare parts rack; 8 -- Stool; 9 -- Armchair. A = Ship's bow.

During their watches, the dosimetrists must perform the following operational functions:

Prior to NPP Startup:

1) prepare all dosimetric apparatus;

2) at the command of the officer on watch, turn on the stationary dosimetric devices for the measurement of levels of radiation and concentrations of radioactive gases and aerosols;

3) record the measurement results in the log according to prescribed form; record the data on the plan of the ship [see note] and report them to the officer in charge. [Note: The plan is a schematic drawing of the ship, and a separate drawing of the reactor section. In checking the radiation state of the ship compartments, the data are recorded on these drawings. The plan is an operational document.

During Normal NPP Operation:

1) immediately following NPP startup, take readings of all stationary dosimeters, record them in log and plan, and report to officer in charge;

2) during the watch (with normal NPP operation) take systematic readings of dosimeters and make proper entries. It is advisable first of all to maintain surveillance over technological dosimetry instruments which should be checked as often as possible. The biological instrument readings can be taken once or twice each watch.

During Abnormal NPP Operation:

Under conditions of abnormal NPP operation, there is usually an increase in radiation levels or the appearance of radioactive gases and aerosols. In this case, there is a triggering of the appropriate signals in the station, and the dosimetrist on watch must immediately take readings of all instruments, recording them in the log and reporting to the officer in charge who will take the necessary measures.

Dosimetry Station Documentation

Normal operation of the dosimetry station and the entire dosimetry service as a whole requires the maintenace of special documentation which contains systematic data on everythingrelating to the radiation state of the NPP vessel.

The documents include:

1) instructions on radiation safety for the personnel operating the NPP;

2) plan of reactor section and adjacent compartments -- logitudinal cross-section and deck plan;

3) table of actual activity of control samples;

4) log journals, including:

a) individual data on irradiation and contamination of personnel;

b) levels of radiation and concentrations of radioactive gases and aerosols beyond the confines of radiation shielding;

c) levels of specific activity of primary NPP loop and its elements;

d) degree of radioactive contamination of compartments and equipment of reactor section, as well as deactivation operations and their results, including a measurement of specific radiation levels of sewage and deactivation waters;

e) maintenance work on instruments and calibration data.

Chapter VII

FUNDAMENTAL SOLUTIONS TO PROBLEMS OF RADIATION SAFETY AND THE SYSTEM OF NPP DOSIMETRY CONTROL ON THE ATOMIC ICEBREAKER "LENIN"

24. Formulation of the Problem of Radiation Safety on the Icebreaker

Radiation control of the NPP on the Soviet icebreaker "Lenin" is maintained by an independent technical service which is a part of the system that works to assure NPP radiation safety -- the Radiation Safety Service (RSS).

The NPP of the icebreaker is planned and constructed in such a way that with normal operation, the appearance of excessively high levels of radiation is excluded; this also goes for concentrations of radioactive materials, not to speak of dangerous levels and concentrations.

In addition, features to combat the possibility of serious troubles involving the rupture of heating element shells and steam generators in the primary loop have also been incorporated. As a result, the maximum possible concentrations of radioactive substances in the air of living quarters over the time necessary to shut down a malfunctioning reactor and appropriate channels will not reach the maximum permissible levels.

The probability of such an accident is very low indeed.

Thus, some increases in the levels and concentrations will indicate only the deteriorating operation of individual NPP elements, e.g.: a small seepage of the primary heat transfer agent, damage in the system for air rarefaction in the reactor section, contamination of ion-exchange and aerosol filters, etc. The ship has a system assuring continuous control of the radiation environment. This system makes possible the early detection of any radiation danger, the determination the locations and causes for its appearance and thus the issuance of instructions for its elimination.

All calculations of the biological shielding, permissible length of presence for personnel in heightened radiation areas, measurement limits, and sensitivity of

instruments were determined on the basis of the maximum possible radiation levels and concentrations of radioactive materials in the controlled zone established by the State Sanitation Inspection [Service].

The thick radiation shielding of the nuclear reactors and their location in a separate section of the icebreaker assure that the non-duty hours of the personnel are spent in a zone where the radiation levels are close to natural background (i.e., the background due to cosmic rays and natural radioactive materials). Over an eight-hour watch, the total irradiation dose does not exceed 0.1 of the maximum daily occupational dose [see note], which is not more than 0.05 reb. The strength of the dose received by the personnel in the working compartments does not exceed 0.5 microrebs/sec. This is 0.3 of the maximum permissible dose for an 8-hour working day. [Note: Here we have in mind the maximum permissible daily dose for persons constantly working with sources of ionizing radiation].

All of the NPP equipment, including the reactors, technological loops, auxiliary mechanisms, circulation pumps, steam generators, filters, and all communications channels are located in the so-called central section (CS). The CS is limited by the primary contour of basic biological shielding and is an isolated section having special ventilation with ejection of air into the outer atmosphere through the rear mast-pipe. The reliable insulation of the central section is assured by a degree of air rarefaction within it which prevents the spread of gas and aerosol activity over the ship in case of its appearance.

Access to the central compartments may be had only through special sanitary cabins in which there is a radiometric survey made of the personnel and their clothing.

At the head of the radiation safety service aboard the icebreaker (RSS) is the Service Chief who has the responsibility of its general and technical direction and is answerable directly to the NPP Chief.

The direction of RSS operations is centralized at the central dosimetry station (CDS) located on the lower deck (starboard), in the neighborhood of the central section (but outside it). The CDS contains all of the secondary measurement and signalling devices which allow the dosimetrist on watch to maintain surveillance of the radiation environment of the icebreaker. The CDS contains the central signal-control dosimetric control panel (SCDCP) which has a mnemonic scheme of the basic communications of all three reactors with the signal lights mounted in the appropriate places. Next to the mnemonic scheme, the panel has a scheme of points for controlling the secondary-loop steam activity and points of air intake for ship ventilation puposes. Partitions in the CDS also contain all secondary control-measurement instruments of individual dosimetric systems, as well as signalling

and communications equipment.

The icebreaker has a color-coded warning system which permits one to gain a qualitative idea as to the character of the radiation danger. The following color code has been adopted: green -- permissible radiation level; yellow -- maximum permissible level of radiation; red -- dangerous level of radiation; violet -- maximum permissible level of concentration of radioactive gases and aerosols.

The color signals appear on the secondary instruments installed in the CDS and the SCDCP. Color signal lights are also installed at the dosimeter pickups. In addition, similar equipment is installed at some entrances to compartments of the central section along with sound warning systems providing personnel with an idea of the state of these compartments prior to their entry. Beyond the CS, such color signals are installed only in the passageways of the upper deck by the living quarters in the area of the reactor section (one on each side).

Upon a change in the radiation environment, a threshold signal is triggered in the warning system; as a result, light and sound signals are produced. The dosimetrist on duty, having heard the bell and seen the signal light, measures the radiation level or concentration of radioactive materials, and makes the necessary decision. The CDS is equipped with a telephone and intercom system which assures efficient control and rapid information to the NPP chief who as a rule is to be found in the power station containing the NPP control apparatus.

If necessary, the dosimetrist on watch sends out the junior dosimetrist to check the radiation environment on the spot or to obtain additional readings with the aid of portable instruments kept in the CDS. The results of all measurements, reasons for changes in the radiation environment, and corrective measures are registered by the dosimetrist in special logs. Regular measurements are taken of radiation levels and concentrations of radioactive materials; the results are recorded on a special plan of the ship showing the controlled compartments of the vessel.

A general view of the SCDCP of the atomic icebreaker "Lenin" is given in Fig 42. Fig 43 shows a photograph of the NPP control panel in the power station.

25. Control of Penetrating Radiation Levels

Gamma Radiation

Gamma radiation levels in the compartments of the central section and adjacent compartments, the icebreaker has stationary indicator and signalling gamma-roentgenometers.

Gamma dosimeter pickups are installed:

in compartments next to the reactor shielding and in the compartment over the reactors which contain the servomotors of the control and protection system which personnel enter periodically to check the automatic apparatus;

along the sides and passageways of the upper deck in the reactor section area;

in the compartment under the reactors -- the so-called thermal control pickup compartment.

The stationary gamma dosimeters on the icebreaker are signalling and indicator instruments with three ranges of dose strength measurement: 0.05-1, 0.5-10, and 1-100 microroentgens/sec.

The warning signal actuation threshold is established within limits from 0.2 to 100 microroentgens/sec, i.e. within the limits of practically the entire measurement range.

The measurement accuracy is one the order of ±10%. As detectors, the pickups employ halogen counters which assure long and reliable instrument service under various temperature conditions.

Neutron Radiation

The sole source of neutrons is the reactor active zone. For this reason, neutron pickups are mounted in the direction of most probable neutron escape -- in the protection and control compartment and under the central section in the thermal control pickup compartment. The pickup of the fast neutron dosimeter represents a high-efficiency scintillation detector of fast neutrons in combination with a photomultiplier. In the neutron energy range of 0.5-20 mev, the effectiveness of registration of fast neutrons, equal to an average of 0.7%, varies analogously to that for human body tissues; this is of extreme importance to the correct evaluation of the biological effect of fast neutrons. Owing to the high sensitivity, the signalling threshold of the fast-neutron dosimeter can be regulated within limits of 3.5 neutrons/cm^2sec to $3.5 \cdot 10^3$ neutrons/cm^2sec. This device is insensitive to strong gamma ray fields of up to 500 microroentgens/sec.

26. Radiometry of Active Materials Beyond the Limits of the Primary Contour (Loop)

As is known, radioactive substances can spread in the form of radioactive gases, aerosols, and beta-contamination of various surfaces.

In planning and designing the atomic icebreaker, special attention was devoted to the provision of various means of controlling the purity of its air both with respect to radioactive gases and aerosols. The gas and aerosol

Figure 42. Dosimetric control panel on the atomic icebreaker "Lenin".

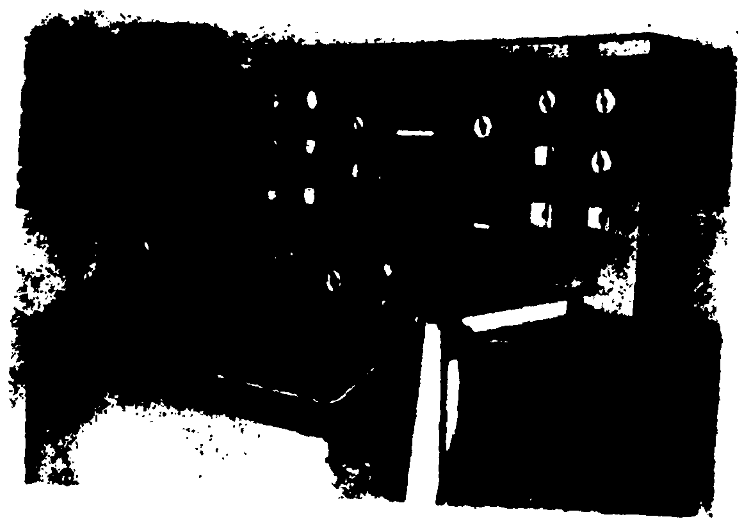

Figure 43. Reactor control panel in the power station of the atomic icebreaker "Lenin".

radiometers were installed for the following purposes:

1) Control of the hermetic seal of the primary loop is maintained with the aid of gamma radiometers whose pickups are installed at most probable leakage points or most effective control points. These are as follows:

main water takeoffs of the auxiliary loop from the filter coolers;

secondary-loop steam pipes after the steam generators;
condensers of main and auxiliary turboaggregates.

These gamma radiometers consititute six-channel instruments with dose measurement limits from 0.1 to 20 microroentgens/sec.

The threshold of warning signal triggering is set within limits from 0.2 to 20 microroentgens/sec. Auxiliary measurement devices are installed in the CDS. A block diagram of these gamma radiometers is shown in Fig 44.

Fig 36 showed a diagram of gamma radiometer mounting on a steam pipe. The high temperature at the surface of the steam pipe insulation (over 50°C) made water cooling of the pickup necessary.

2) Control over the air-steam mixture in the turbogenerator condensers is realized with the aid of gas beta radiometers. Upon disruption of the hermetic seal of the steam generators, the gaseous fission fragments -- krypton, xenon, et al., -- will unavoidably enter the steam in the secondary loop along with the primary heat transfer agent and be fixed by the radiometers. With the aid of these gas beta radiometers, it is possible to spot the faulty steam generator rapidly and shut it off.

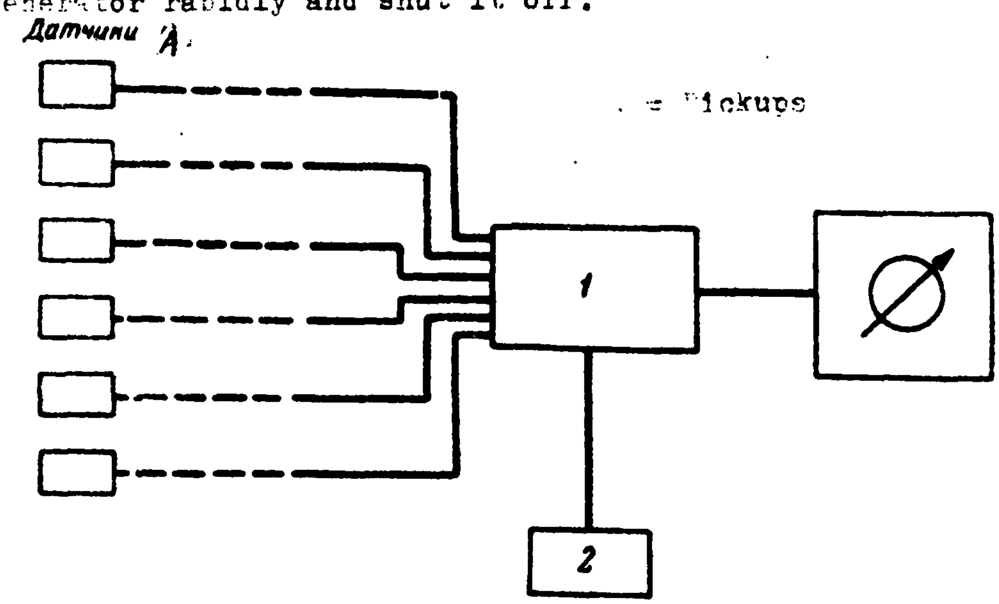

Figure 44. Block diagram of six-channel gamma radiometer.
1 -- normalization and signalling block; 2 -- feeder block.

3) Control over primary-loop leakage is maintained likewise by measuring the concentration of radioactive aerosols in the air of the central section compartments, which is done with the aid of special radioactive aerosol radiometers.

As the continuous-control radiometers, the icebreaker has flow-through beta radiometers whose pickups are mounted are mounted in the ventilation ducts from the steam generator and main circulation pump compartments and the compartments containing the protection and control apparatus and thermal control pickups. In the first group of these compartments, the devices are intended to measure the rigid beta-radiation from N^{16} nuclei and operate in the range from $5 \cdot 10^{-6}$ to $5 \cdot 10^{-10}$ curie/liter with a gamma-radiation background of up to 0.02 microroentgens/sec. In the second group of compartments, the presence of a leak from the first loop, the air activity is determined mainly by the fission fragments or the activated corrosion products of the primary-loop steel (chromium, manganese, nickel, and iron). For this reason, the pickups of the flow-through gas dosimeters at these points will be acted upon by beta particles of a wide energy range. In a number of cases the pickups are installed in specially-widened portions of ventilation channels ("counting" enclosures) whose size and shape were calculated theoretically in advance.

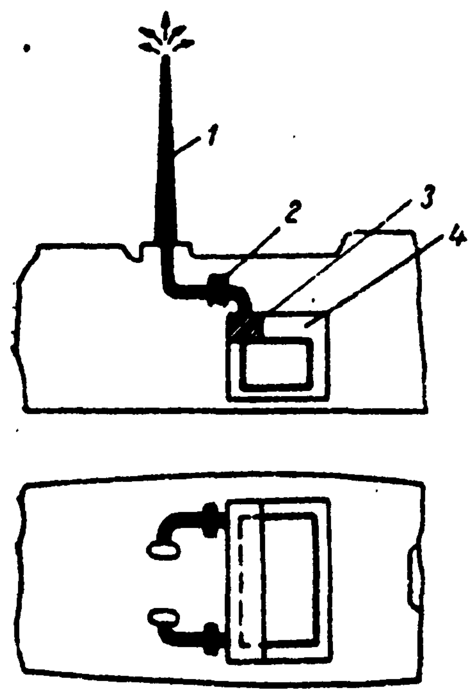

Figure 45. Diagram of air ejection through mast.
1 -- Mainmast; 2 -- Filter; 3 -- Central section; 4 -- Ventilator cubicle.

The ventilation ejector pipes are brought out along the side of the ship into the mainmast of the icebreaker which is a hollow Л-shaped tube about 23 meters in height. Both ejector channels contain flow through gas beta-radiometers. In addition, a certain portion of this air flow is continuously pumped through the ionization chamber of a "Cactus" device which permits additional control of the specific activity of ejected air.

Figure 45 is a diagram of the air ejection channel from the reactor section through the ventilation and mainmast.

The icebreaker likewise has a system of radiometric instruments for periodic measurements of aerosol concentrations in the air of reactor section compartments. The operating principle of this system is described in Chapter IV.

The air samples for periodic measurement of aerosol concentrations are taken from the following compartments:

the stem and stern compartments containing the main and emergency circulation pumps;

thermal control pickup compartments;

ballast pump compartments;

protective and control equipment compartments.

In addition, control is maintained over the air in the ventilation systems along which the air is pumped from the reactors. The air is likewise sampled ahead and in front of the anti-aerosol filters, which makes it possible to assess their operation and the extent of failure to remove radioactive materials.

The pickups of the system of radiometric aerosol control, flow meters, and electromagnetic valves are located in a special ventilation compartment in the central section area, whose air is likewise ejected through the mainmast.

Fig 14 shows a longitudinal cross-section of one of the reactors which makes it possible to trace the movement of the heat transfer agent in the primary loop. From reactor 1 the bidistillate moves through two pipes to generators 2 and then to circulation pumps 3, through which it returns to the reactor, closing the primary loop. In addition, there are auxiliary branchings from the primary loop to filters 5, emergency circulation pumps 4, and then to the pump motor cooling coils.

The basic discontinuous joints on the primary-loop equipment which may give rise to leakage of the radioactive heat transfer agent are the reactor tops, protective and control rod drives, slide gaskets, volume compensators, main ciculation pumps, and emergency circulation pumps.

Near these joints are special leakage collectors.

The icebreaker features continuous control of the active heat transfer agent and periodic measurements of its components:

a) with respect to the intensity of gamma radiation of the heat transfer agent, analogously to a multi-channel technological gamma radiometer.

The pickup in this control system is mounted on the primary-loop bypass at a point where the rigid gamma background due to oxygen activity is significantly lowered. The secondary block of this measuring instrument, as all others, is installed in the ODS;

b) with the aid of periodic radiochemical analysis of heat transfer agent samples carried out in the radiochemical and radiometric laboratories of the icebreaker.

In practice it is assumed that the attainment of bidistillate activity of 10^{-2} curie/liter indicates an NPP emergency; however, exploitation can be continued to a level of 10^{-1} curie/liter in the absence of dangerous leaks as determined by the above methods.

27. Radiometry of Sewage Water from Reactor Section

All waters contaminated by radioactive materials are stored aboard the icebreaker; they are collected in special tanks.

Among these waters are highly-active water (heat transfer agent) from the primary loop and low-activity waters from the deactivation of compartments, equipment, clothing, and bathing of reactor-section staff. The specific activity of these waters on the icebreaker as a rule does not exceed 10^{-2} curie/liter for a highly-active primary heat transfer agent and 10^{-6} curie/liter for low-activity waters. The former is treated in a special purification plant aboard ship which employs ion-exchange filters.

To measure the specific activity of sewage waters, special gamma radiometers are installed on the vessel. The determination of specific activity by gamma radiation turned out possible inasmuch as it was shown experimentally that the composition of radioactive contamination in the distillate, and therefore the ratio of beta and gamma intensities are practically constant for a wide variety of NPP operating regimes.

The gamma radiometer pickups are installed before and after the sewage filter and make it possible not only to determine the specific activity before and after filtration, but also the efficiency of the filter.

Guided by the readings of these gamma radiometers, the icebreaker's dosimetry service can if need be determine the necessary degree of dilution of sewage waters before disposal overboard. It should be noted however that the disposal of waters overboard is employed only under exceptional circumstances (and in strict accordance with international regulations when these are promulgated), far from shores and fishing waters.

With normal NPP operation, such a need does not arise, and the capacity of the sewage tanks is sufficient to hold all the liquid wastes from the central section over the entire voyage of the icebreaker.

28. Radiation of the Non-Technical (Bytovaya) Ventilation System

The non-technical ventilation system of the icebreaker draws air from several points at the upper-deck level. In case of NPP malfunctions, when the air ejected from the central section through the mainmast can have a specific activity over 10^{-9} curie/liter, it is necessary to control the specific activity of air taken in by the ventilation system. For this purpose, at all points of entry of fresh air the icebreaker has pickups for measuring gas activity described above. The pickups are installed in the ventilation ducts, while the measuring instruments are usually in the CDS.

In accordance with calculations, even in the case of an unfavorable NPP regime, the concentration of radioactive gases in air entering the compartments will not exceed 10^{-10} curie per liter due to natural dilution, which is not higher than the maximum concentration of argon-41 for living quarters.

29. Radiometry of the Surface of the Body, Clothing, Footwear and Individual Dosimeters

In the sanitation cabit at the exit of the central section there is a local stationary beta radiometer which monitors the beta contamination of the surface of the body, hands, feet, and clothing of each staff memeber leaving the section. Analogous devices are installed in the special laundry and pressing room for controlling the deactivation of protective clothing and weeding out contaminated items.

As beta detectors these pickups employ halogen counters. The instrument permits measurements within limits from 1 to 10^6 beta-particles/min·30 cm^2.

All of the personnel working in the central section are provided individual dosimeters by means of which they control their total radiation dose. These portable devices include:

1) pocket electroscopes with a range of up to 200 milliroentgens and visual scale;

2) KID-4 pocket dosimeters with two ranges: up to 200 milliroentgens and 2 roentgens. The device operates on the principle of condenser discharge in an external radiation field. The chamber readings are registered with the aid of a device in stalled in the CDS;

3) the film badge -- a plastic translucent casette containing a piece of film of a certain sensitivity. The

degree of irradiation revealed upon development is proportional to the total dose. This method makes it possible to measure a total dose of up to 15 roentgens;

4) the "nutcracker" signalling gamma radiometer which emits a clicking signal proportional to the gamma intensity; the clicks are heard in the headphone and a flashing light provides a further means of indication.

Among the individual dosimetric devices is likewise the gamma radiometer installed in the icebreaker's medical block which measures the concentration of iodine-131 in the thyroid. The high-sensitivity scintillation detector of this radiometer in combination with the photomultiplier makes it possible to measure iodine-131 from its gamma radiation with a sensitivity of 0.02-0.04 microcurie, which is equivalent to 1/5-1/10 of the maximum permissible content of this isotope in the human organism.

30. Portable Dosimeters

In addition to the stationary dosimeters installed on the icebreaker, there are a number of portable dosimeters and radiometers which are used to carry out various supplementary and control measurements of gamma radiation, fast neutron streams, and the beta contamination of surfaces and equipment.

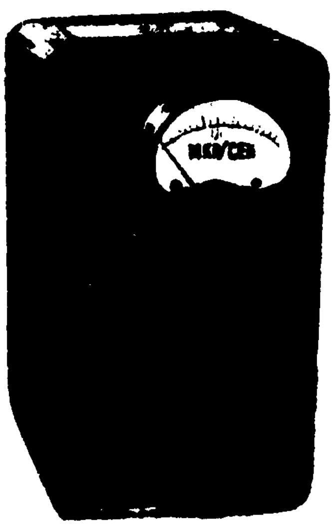

Figure 46. Portable device for measuring gamma-radiation levels (PMR-1 type). Scale graduated in microroentgens/sec.

Among the portable devices are:

1) a gamma dosimeter with measurement limits from 0.1 to $16 \cdot 10^3$ microroentgens/sec;

2) a fast-neutron dosimeter analogous in specifications to the stationary instrument;

3) rod-type beta-gamma radiometer with which the dosimetrist can measure beta streams and gamma radiation doses. This device is employed by the dosimetrist on duty in checking the contamination of equipment, mechanisms, and deck and wall surfaces.

The instrument has the following ranges: from 1 to 10^6 beta particles/min·30 cm^2; for gamma radiation -- from 0.1 to 2000 microroentgens/sec.

The portable instruments are kept in the CDS.

Fig 46 shows a portable dosimeter for measuring gamma radiation levels.

Figure 47. The atomic icebreaker "Lenin".

Conclusion

An operational check of the entire dosimetric system of the icebreaker was carried out during its first arctic voyages in 1960 and 1961. The comprehensive and careful program of tests showed that the dosimetry service was successful in fulfilling its technical tasks and was capable of assuring total control of the radiation environment of the ship.

Fig 47 is a photograph of the icebreaker "Lenin".

Chapter VIII

SOME INFORMATION ON RADIATION SAFETY MEASURES ON FOREIGN SHIPS WITH NPP

31. The Passenger-Cargo Ship "Savannah"

This section contains some data on the freighter "Savannah" being built by the US. Unfortunately, the published data are of a general character and do not contain a full description of the dosimetric control system.

This ship uses a water-water reactor with a fuel consisting of uranium dioxide (UO_2) with a 4% enrichment with U-235.

The general plan of the ship indicates that the reactor section is located in the middle portion of the hull ahead of the engine room containing the main turbines and all of the auxiliary secondary-loop mechanisms. The NPP reactor is surrounded by primary radiation shielding which lowers the streams of penetrating radiation down to permissible levels for the strict-regime zone. For the purpose of lowering the strength of the dose in the compartments next to the reactor, the basic primary-loop equipment (pipes, steam generators, and primary-loop circulation pumps) and a considerable portion of the ausiliary equipment are enclosed in a secondary shield of cylindrical form. It is interesting to note that the weight of the shielding is about 50% of the weight of the nuclear power plant.

The dosimetric control system. The control of radiation levels and concentrations of radioactive gases and aerosols on the ship, it is equipped with dosimeters permitting the following types of control:

a) fragment activity of the primary-loop heat transfer agent;

b) activity of water in the steam generator capable of arising due to primary-loop leakage;

c) activity of water in the auxiliary loop capable of arising due to leakage from the structural elements of the primary loop;

d) activity of water at filter takeoffs indicating

a reduction of filter efficiency and the necessity to replace the resin filter;

e) activity of air in the reactor section with respect to aerosols which can arise as a result of primary-loop leakage;

f) levels of penetrating radiation in various ship compartments.

The dosimetric apparatus includes the following instruments.

Stationary instruments of the radiation safety service (biological dosimetry). These devices have three measuring channels, two of which are equipped with six pickups located in various ship compartments which measure the levels of ionizing radiation. On the control panel, in addition to the indicators, are recorders which continually record registration levels. The third channel has three pickups which are used to determine the possibility of access inside the biological shielding and the filter compartment.

Stationary technological dosimetry devices. The instruments have five measuring channels. The first of these (channel No 4) is equipped with five pickups controlling the leakage of active water from the primary loop into the secondary one. The second and third channels (No 5 and 6) each with one pickup measure the activity of water in the second loop for the purpose of detecting leakage from the primary loop. Channel No 7, also with one pickup, is used to register the appearance of radioactive fragments from damaged heating elements in the primary-loop heat transfer agent. Channel No 8 is so determine the state of ion-exchange filters and indicate the necessity of replacing filter elements upon saturation with radioactive materials.

Stationary devices for controlling radioactive gases and aerosols in the ventilation air. These devices have eight measuring channels with one pickup in each channel. Four of them (No 9, 11, 13, and 15) are intended to measure radioactive aerosols, and the others (No 10, 12, 14, and 16) to measure radioactive gases.

Under normal conditions the gaseous wastes are ejected into the atmosphere through the hollow mast. For the case where the active gas exceeds the maximum permissible level, it is possible to dilute it with fresh air to the required concentration or purify it of radioactive inert gases with the aid of a special facility for this purpose.

Portable dosimeters. The ship has a full complement of portable devices for controlling and studying various types of ionizing radiation at any point on the ship and determining integral radiation doses in the strict-regime zone.

The plans incorporate a warning system brought out onto the main NPP control panel.

Table 15 gives plan data on the expected radiation levels in the various compartments of the "Savannah". From it we see that the calculated levels are camparable to the the level of the natural background radiation.

Table 15

Calculated Radiation Levels in the Compartments of the Atomic Freighter "Savannah"

Location of compartment	Working conditions	Access to compartment	Calculated dose of irradiation
Passenger compartments	Normal	Any time	500 millirebs per year
Crew compartments	"	Closed to passengers	5 rebs per year
Compartments outside secondary radiation shielding	"	Limited	100 microcuries/meter per week
Inside secondary radiation shielding	When reactor operative	Off limits	Very high
Same	Reactor operating over one half hour	Limited	200 microcuries/meter per week
Reactor sections during refueling	Reactor operating over 10 days	"	Controlled by dosimetrist
Cargo holds	1/5 maximum power	Not limited	1500 millirebs per year

<u>Heat transfer agent purification</u>. To maintain the purity of the primary-loop heat transfer agent, the "Savannah" is to have a special water purification system. It must assure the removal from the primary loop of all foeign impurities and insoluble solid particles, including products of metal erosion and corrosion, as well as fission fragments which can enter the primary loop upon damage to the heating element shells. The plan likwise envisages the installation of ion-exchange filters.

<u>Removal of radioactive wastes from the ship</u>. The NPP plan of the "Savannah" includes means of removing radioactive wastes from the ship during operation -- liquid wates (radioactive waters), air from the reactor section, and

ventilation gas from the radioactive water sotrage tanks. The radioactive air will be ejected through one of the masts after passing through aerosol filters. Various radioactive waters must be drained into special cisterns. The latter are equipped with sufficient radiation shielding which assures the possibility of retention of radioactivity of considerable levels (emitting doses of up to 300 milliroentgens/hour).

The active primary-loop heat transfer agent can also be drained into a special cistern.

The entire system for radioactive waste disposal is planned in such a way that the presence of fission fragments in the liquid wastes will not hinder the explcitation of the NPP.

The overboard disposal of liquid radioactive wastes will be made possible, although the builders point out that it will be employed only upon the promulgation of the relevant international rules permitting such operations. Up to that time, the "Savannah" will dispose of its radioactive wastes with the aid of a specially planned and constructed barge designed for offshore operation and having the following basic specifications:

Length, meters....................................	39
Width, meters.....................................	11
Draft with full load, meters......................	4.4
Working displacement, tons........................	~760
Radiation shielding weight, tons..................	~250

The ship must have facilities for the servicing and ,aintenance of reactors, receiving, treatment and sorting of nuclear fuel remnants and all other radioactive wastes. The hold has strict-regime compartments (the "dirty" zone), radioactive water tanks, and heating element and control rod compartments. Above these are the engine room, maintenance shops, and storerooms. These can be deactivated if the need arises. The superstructure contains the living and non-technical (bytovyye) compartments, as well as the control post. The entire superstructure is a "clean" zone. Loading and unloading of heating elements on the "Savannah" is carried out by means of a 9-ton crance mounted on its upper deck. The "dirty"-zone compartments are equipped with a separate ventilation system. Air is removed through filters. The air radioactivity is controlled by means dosimeters. Purified water can be taken back aboard the "Savannah". A number of operations are, automated. The ship is staffed with 15 technicians.

32. US Nuclear Submarines

The material in this section is taken from foreign journals [see note] and somewhat exceeds the limits of our

work due to the specificity of radiation safety problems on nuclear submarines. Indeed, in the submerged state the submarine is totally isolated. There is no opportunity for air ejection or the disposal of radioactive gases and aerosols. In addition, the weight limitations and internal dimensions of submarines require the greatest possible limitation of the size and weight of radiation shielding. These requirements impose rigid specifications on the NPP with respect to radiation safety. Esentially, the radiation environment of a nuclear submarine determines its basic characteristic -- underwater autonomy. Under these conditions dosimetric control which determines the possibility of prolonged presence of personnel in sealed compartments assumes great importance. [Note: Medical Technical Bulletin, No 6, 1955; "The Power Plant of the Nuclear Merchant Ship N.S.", Journal of the American Society of Naval Engineers, Vol 70, No 4, 1958; US Armed Forces Medical Journal, No 6, 1958; "Nuclear Power Design", Canadian Shipping and Marine Engineering News, Vol 29, No 10, 1959.]

The first US nuclear submarine, the "Nautilus" uses a heterogeneous water-water slow-neutron reactor. The "Sea Wolf" had an experimental reactor using liquid sodium as the heat transfer agent. However, tests showed the unsuitability of the sodium system due to the great gamma activity which led to a considerable increase in weight and size of the radiation shielding and the dangerous properties of sodium -- combustion in air and violent reaction with water. These drawbacks led to over-irradiation of the crew due to NPP malfunctions [see note]. In the future, reactors with liquid sodium were replaced by standard water-water reactors. [Note: See the pamphlet by I.A. Bykhovskiy, Atomic Submarines, 1957, and Atomic Ships by the same author, Sudpromgiz, 1961].

On the basis of data appearing in the foreign press, it is possible to conclude that nuclear submarines have both stationary and portable dosimetric instruments. Nuclear submarines have special radiochemical laboratories for the detailed study of radiation environments. These contain various radiochemical and dosimetric instruments, equipment for radiochemical analyses, photodosimetry, control samples for calibration, etc.

Taking into account the great importance of controlling internal radiation on nuclear submarines, the US vessels employ systems for continuous measurement and recording of air activity. With an increase of specific air activity over the permissible level, there is a triggering of special light and sound signals. In addition, air samples are taken systematically with the aid of portable equipment with subsequent analysis in the radiochemical laboratory.

The control of beta contamination of compartment surfaces, equipment, clothing, food, and bodies is maintained

with the aid of special beta dosimeters.

In addition to stationary dosimeters for measuring penetrating radiation which are installed in all of the main submarine areas adjacent to the reactor section, there are likewise portable dosimeters, including film dosimeters which make it possible to register all types of radiation. Instruments which signal the leakage of the heat transfer agent from the NPP primary loop are also included.

According to data published by the US AtomicEnergy Commission, the maximum permissible dose of nuclear submarine personnel is 300 millirebs/week. According to the same source, the radiation levels are about 4% of the permissible ones, reaching a possible value of 40% of the same levels [see note]. However, these figures should be regarded with caution, since it is known that the "Nautilus" has had to replace some of its crew members as a result of excessive irradiation during the operation of the submarine, while the "Sea Wolf" even had human casualties as a result of a malfunction of the sodium reactor. [Note: New England Journal of Medicine, 1957, No 2].

Much attention is devoted to the regeneration and filtration of air on US submarines due to the difficulty of these problems. It has been reported that special electrostatic filters to remove aerosols from the air are installed in the ventilation ducts. Detailed data on this apparatus have not been published. Also unclear is the problem of the disposal of active water formed in personnel and equipment deactivation, as well as in the washdown and liquidation of heat transfer agent leaks.

The following fact was established on the "Nautilus". The presence in the compartments of instruments covered with luminous materials sharply increases the specific concentration of radioactive aerosols and gases. As a result, the dosimeters give incorrect readings. All scales and faces, including wristwatch faces, had to be replaced.

All of the above, despite the inadequacy of the published material, indicates the great technical difficulties arising in the assurance of radiation safety aboard US nuclear submarines.

Conclusion

The development of nuclear physics is proceeding at such a fast rate that the task of designing of NPP for all types of transport is becoming quite timely. It can be assumed that the time is not far off when a nuclear-powered aircraft will become a reality. We are already summing up the results of the first arctic cruises of the atomic icebreaker "Lenin". Soon the US will publish data on its nuclear freighter "Savannah". There is every reason to expect the expansion of

NPP application on various types of vessels.

One of the basic problems in the practical operation of NPP is the problem of assuring radiation safety. In this book we have examined radiation safety and dosimetric and radiometric control on NPP ships. These problems are general in all cases of nuclear power application, but their concrete realization depends in each individual case on the specific conditions of NPP exploitation.

For example, it is considerably simpler to assure radiation safety at stationary electric power stations than on ships, inasmuch as in the first case there are no rigid limitations imposed on weight and dimensions.

The first steps toward the development of radiation shielding on a nuclear vessel must begin with a study of the possibility of emergence of radioactivity of all types, and an examination of the composition of radioactive materials with respect to isotopes. It is necessary here to take into account both normal reactor operation and emergency conditions. The radiation shielding scheme and dosimetric control must be devised with due regard for the general arrangement of ship compartments and ship design in general.

The accumulated theoretical and practical experience of world reactor design and technology, as well as the experimental exploitation of the icebreaker "Lenin" give every reason to assume that the use of NPP on ships is quite possible from the standpoint of radiation safety provided that there is strict compliance with a number of requirements which are common for all NPP.

We shall now attempt to briefly summarize these requirements:

1) All reactor and loop structures as sources of penetrating radiation must be enclosed by shielding. The shielding thickness is calculated in such a way that with maximum power NPP operation, the gamma radiation not exceed the background level due to the radioactivity of the nearby air and water as well as cosmic radiation. The shielding must not allow penetration by direct gamma-ray and neutron streams.

2) NPP in combination with all of its elements must be isolated from all other ship compartments. This will reliably prevent the emergence of radiation in any form. The design and quality of insulation must be such that radiation might not emerge even by means of gas diffusion. This is easily achieved by the maintenance of a certain degree of rarefaction within the reactor section. All NPP ventilation systems must be fitted with anti-aerosol filters with a high accumulation coefficient.

3) The dosimetric and radiometric control system must assure reliable, continuous control of the hermetic seal of the primary NPP loop.

4) All nuclear vessels must have maximum unsinkability to assure that they remain afloat. However, in the case of disaster, the shielding structures and all NPP elements must retain their hermetic seal, even upon submersion to fairly large depths in order to prevent the contamination of the seas with radioactivity. In this connection it is necessary to note that the problem of preserving the "purity" of the world ocean and the atmosphere is now assuming exceptionally great importance.

5) Access and egress from the strict-regime zone must be only through a special hatch equipped with radiometric and dosimetric control instruments, as well as deactivation equipment.

6) The dosimetric and radiometric control system must assure simultaneous automatic control and recording with respect to the main types and points of radiation with a maximum degree of centralization.

7) As a rule, dumping of radioactive wastes overboard should not be permitted except in instances covered by international rules. The nuclear vessel must have special shielded containers for the collection and storage of liquid radioactive wastes.

8) Equipment in the strict-regime zone must be amenable to deactivation. In a number of cases, particularly with a complex equipment configuration, it should be covered with special plastic jackets easily subject to deactivation.

9) In designing nuclear vessels, it is desirable to remove the reactor section as far as possible from living quarters, especially from the galley and medical compartments. This is most easily achieved with abaft placement of the reactor section.

10) In NPP maintenance and reactor fueling -- the replacement of used-up heating elements -- there should be strict observance of all rigid-regime zone conditions in order to avoid the spread of radioactivity.

All of the difficulties involved in the assurance of full NPP radiation safety on ships can be eliminated by means of a well-thought-out appraoch to design and exploitation. The subsequent development of nuclear power production will lead to the introduction of new, improved reactors which assure better radiation safety conditions. There will be a parallel development of NPP shielding and control methods, which will also simplify radiation safety.

We can attempt to look into the future of NPP. We are about to see the development of a nuclear technology based on controlled thermonuclear reactions. This new field based on the energy released in the synthesis of light nuclei promises to mankind a practically unlimited source of fuel -- the waters of the world ocean which will last many millions of years.

The scientific and technical forces of the Soviet Union, which hold a deservedly leading position in the world, are successfully solving the problem of conquering the forces of nature in the name of the bright future of humanity.

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